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20th and 21st Century Sea-Level Variability in Winyah Bay, SC

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20th and 21st CENTURY SEA-LEVEL VARIABILITY IN WINYAH BAY, SC

Submitted by

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ABSTRACT

The study of historic sea-level variability has important implications for understanding ongoing and future changes in relative sea level in the central South Carolina region. This knowledge is important in regards to multiple potential impacts on coastal areas that rely heavily on waterfront activities – socio-economically, culturally, and ecologically. The site of this project, Georgetown County, South Carolina, is widely exposed to these coastal impacts.

This project utilized a historic hand-written tide-gauge record from 1899-1904 and a modern water-level logger installed at the same location in October 2018 to investigate the 20th and 21st century sea-level rise in Winyah Bay. Vertical land motion, oceanic variations and global sea-level rise were differentiated to investigate changes in the rate of relative sea-level (RSL) rise on a decadal time scale and to distinguish between regional spatial differences in the rates of relative sea-level rise. Fluvial discharge, precipitation and tidal data collected at several stations throughout the coastal plain were analyzed to characterize inter-annual and seasonal fluctuations in RSL and how those mechanisms contribute to flooding in the local community. Finally, land elevation measurements from areas in the City of Georgetown that are vulnerable to flooding were used in conjunction with nuisance flood modeling to identify timing and duration of local flood inundation. The historic and modern sea-level records were used to identify seasonal trends as well as how vulnerability to flooding at these locations has changed and will continue to change over time with continued RSL rise.

Results of this study show that RSL has risen in Winyah Bay *0.55± 0.066 m between 1899 and 2019*. A long-term average linear rate of RSL rise for this area is *4.6 ± 0.6*

mm/year, which is higher than nearby gauges in Wilmington, NC (2.47 mm/year) and Charleston, SC (3.32 mm/year). These regional differences are most likely due to differences in vertical land motion.

On an inter-annual scale, climatic cycles control changes in precipitation and the resulting fluvial discharge volume contributes to changes in RSL regionally. On a seasonal scale, tides and discharge also contribute to temporary changes in RSL and these seasonal cycles determine during which months 'nuisance' flooding occurs more severely in the City of Georgetown.

Modeling of predicted tides and yearly mean RSL shows that nuisance flooding did not occur in 1899-1900 in the City of Georgetown due to tides and sea-level alone, however, tides and mean RSL in combination with wind and discharge would have produced minor flooding events. Nuisance flooding in downtown Georgetown (901 Front Street), increased from 4 days to 42 days within the three years from 2017-2019 only due to inter-annual variability in RSL. Projections show that nuisance flooding will occur almost every single day of the year from tides alone at some locations in the City of Georgetown by the year 2039. Precipitation, fluvial discharge, oceanic currents and tidal node cycles could also contribute further to higher base RSL and accelerate the timeline for flooding. With this result, solid planning is required soon in order to protect homes and businesses in vulnerable areas. These results contribute to the understanding of spatial variability of RSL rise along the U.S. East Coast and they may be considered in local policy and management decisions.

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INTRODUCTION

Global sea level has been rising for the last 12,000 years at varying rates and has increased during the 20th and 21st centuries. Rising sea levels along the coast present enormous consequences for ecosystems, societies, and economies all over the world. 10% of the world's population live in coastal areas that are vertically within 10 meters of mean sea level (McGranahan et al., 2007). The International Panel on Climate Change predicts a rise in global mean sea level of 40-130 cm by 2100 (Church et al., 2013; Horton et al., 2020). Sea-level rise will continue to progressively cause erosion, encroachment, flooding and salt water intrusion (FitzGerald et al., 2008; Nicholls and Cazenave, 2010). These sea-level changes and associated effects do not occur uniformly, but rather vary on regional to local geographic scales all along the coast as well as over various temporal scales because of vertical land motion and variations in oceanic and climatic drivers such as currents, density, salinity, temperature and local wind (Levermann et al., 2005; Engelhart et al., 2009; Engelhart and Horton, 2012; Ezer et al., 2013). The study of regional to local historic sea-level variability has thus important implications for understanding ongoing and future changes in sea level for coastal management and resiliency efforts.

Georgetown, South Carolina is a coastal lowland county rich with historical sites and industrial activity, both of which would be greatly affected by sea-level rise (Fig. 1). Currently, there is little recent data about the rate at which sea level is changing in the region. Regional studies that have reconstructed relative sea-level rise from the past 4,000 years have found spatially variable results (Van de Plassche et al., 2014). Tide gauges have measured historic sea-level rise in Wilmington, North Carolina (2.47 cm/10 years; 157 km to the north of Winyah Bay) and Charleston, SC (3.32 cm/10 years; 88 km to the south of Winyah Bay) since the early 1900s. There is currently no similar continuous record for Georgetown and Winyah Bay. Georgetown is a community with much of its economic activity occurring close to the water, including the steel mill, paper mill, tourism, and the historic working waterfront. Georgetown County has a population of 61,607 (as of 2017) and is socially, economically and culturally highly diverse (U.S. Census Bureau, 2018). Over 60% of the population of the county lives within the beachfront, riverfront, and tide-land communities of Murrells Inlet, Pawleys Island, Litchfield Beach, and Debordieu Colony (Fig. 1; Cutter et al., 1997). These communities face property value reduction and infrastructure damages due to encroachment of rising sea as well as flooding from the tidally influenced rivers. In comparison to the entirety of Georgetown County where the poverty rate is 19.7%, the City of Georgetown has a poverty rate of 37.1%. Many of the economically and socially disadvantaged communities in the City of Georgetown exist in low-lying areas that are most vulnerable to the effects of sea-level rise (U.S. Census Bureau, 2018).

This research project uses historic and modern tide-gauge data sets to produce specific sea-level data for Georgetown/Winyah Bay. The goal of this study is to provide quantitative context for future changes by examining how much sea level has risen since 1899 in Georgetown and how this compares to similar records from the neighboring regions (southern North Carolina and southern South Carolina). This project then analyzes processes (such as fluvial discharge, precipitation, tides and coastal oceanic variations) that may contribute to local relative sea-level rise and how these factors may affect the vulnerability of the City of Georgetown to flooding.

BACKGROUND

Eustatic Sea-Level Change

Natural sea-level changes occur at a global extent related to changes in ocean volume and at regional to local scales due to vertical land motion (Church and White, 2011). The main mechanisms that drive the current *eustatic* (global) sea-level rise are thermal expansion of sea water due to ocean warming and atmospheric warming as well as the melting of land ice (Nicholls and Cazenave, 2010). Sea level has, in result, been rising globally at a rate of about 1.7 mm/year since 1880 (Church and White, 2011). Sea-level changes have been studied extensively for the past 50 years, with focus originally on long-term eustatic sea-level records. The variability was studied using benthic foraminifera oxygen isotope records, ice shield volume calculations, and coral reef terrace dating (e.g., Chappell and Shackleton, 1986; Fairbanks et al., 1989; Andersen et al., 2004). Global sea level has been studied through the use of global tide-gauge networks and the use of satellite imagery since the late 19th century (Church and White, 2006, 2011; Cabanes et al., 2011). Many tide-gauge records (as many as 6,500 records from the U.S. alone) remain un-discovered, un-digitized, and thus excluded from a comprehensive, modern data interpretation (Talke and Jay 2013; Talke and Jay, 2017).

Relative Sea-Level Change

On a regional to local scale, *relative* sea level (RSL) is influenced by vertical land motion caused by tectonics, glacial-isostatic adjustment (GIA), and sediment loading and compaction (Peltier, 2004; Rovere et al., 2016; Karegar et al., 2016). In addition, anthropogenic wetland drainage and groundwater extraction contribute to coastal land lowering

(Syvitski et al., 2009). Recently, various studies focused on regional RSL change throughout the Holocene and the historic past. Global sets of tide-gauge records have been used to extract a local RSL signal (Church and White, 2006; Jevrejeva et al., 2008; Talke et al., 2018). The study of individual historic tide-gauge records is an important method used to study local and regional RSL (Zervas et al., 2013; Talke and Jay, 2017; Talke et al., 2018). Intertidal foraminifera have been used to reconstruct RSL from Florida to Maine, which has led to a comprehensive picture of RSL variability latitudinally (Fig. 2; Englehart et al., 2009). The closest place to South Carolina this method has been used in detail is located along the coast of North Carolina where RSL was reconstructed for the past 3,000 years (Van de Plassche, 2014; Kopp et al., 2015; Kemp et al., 2017). Kemp et al. (2017) demonstrated RSL rise varied between sites in the Outer Banks on a scale of 0.1-0.2 mm/year over a distance of approximately 100 km due to GIA. Their record showed that RSL rose 0.9 mm/year from 0 to 1800 CE and then increased continuously to 2.4 mm/year presently. This was the fastest increase on a century scale throughout the 3,000-year-record. Van de Plassche (2014) also notes spatial variation of 0.2 mm/year in the rate of RSL rise but on a larger scale over several hundreds of kilometers (from southern North Carolina to southern South Carolina). This study attributes the regional variations in Holocene rates of RSL rise, as well as a lower rate of 20th century RSL rise in Wilmington, NC, to uplift of the Cape Fear Arch. Some of these studies have used intertidal foraminifera method to relate geologic reconstructions and historic instrumental data by connecting these longer scale reconstructions to recent measurements of RSL. These studies often note a faster rate in RSL rise during the last few centuries. (Donnelly et al., 2004; Jevrejeva et al., 2008; Kemp et al., 2009; Talke et al., 2018).

Components of Local Relative Sea Level

Tides are an important factor that can change daily RSL about 1 to 5 m on average globally at the coast (Griffiths and Hill, 2015). Tidal oscillations, which are controlled by the rotation of the earth and the gravitational attraction of the Sun and Moon, can be broken down into a set of periodic tidal constituents that are unique to a given location (Doodson, 1921; Pugh, 1987). These constituents are quantified in terms of amplitude (height) and phase (timing) (Doodson, 1921; Pugh, 1987). The constituents that play the largest role in producing diurnal and semi diurnal tides are: O_1, K_1, N_2, M_2, and S_2 (Talke and Jay, 2020). The M_2 and K_1, constituents are altered by smaller (and more difficult to resolve) constituents to produce an 18.61-year nodal cycle (Doodson 1921; Talke and Jay 2020). The nodal cycle, which can alter tidal amplitude by about 3%, is important to consider when observing RSL over multiple decades (Gratiot et al., 2008; Haigh et al., 2011; Baart et al, 2012). Environmental (altered water mixing dynamics, altered water stratification) and anthropogenic (dredging, land reclamation, and jetty construction) changes to coastal areas can also alter tides and tidal constituents (Talke and Jay, 2020).

There are several atmospheric and oceanic variations that also contribute to RSL change. Atmospheric and oceanic factors driven by climate, such as North Atlantic Oscillation (NAO), Atlantic Meridional Overturning Circulation (AMOC) and ‘inverse barometer effect’ have been shown to cause elevated RSL on inter-annual to multidecadal time scales (Smeed et al., 2014; Piecuch and Ponte, 2015; Pietrafiesa et al., 2015). Goddard et al. (2015) showed that a significant increase in RSL from 2009-2010 was due to a weakening AMOC and a significantly negative NAO index. Variations in the current velocity and geographic path of the Gulf Stream can cause a change in the “tilt” of RSL, changing its elevation at the coast (Ezer and Atkinson, 2015). The Gulf Stream has been shown to have a 6-8-year oscillation in intensity (Ezer et al., 2013). A recent weakening trend in the Gulf Stream may also play a role in causing an increased rate of RSL rise over the last few decades (Ezer et al., 2013).

Implications of Relative Sea-Level Rise

RSL rise has important implications for both the health of coastal ecosystems and socio-economic governance. Marshes, which act as the buffer for many coastal communities against storm surges and stabilize coastal barrier island systems (Duarte et al., 2013; Walters et al., 2014), develop from a natural balance between sediment accretion and RSL rise. This balance can deteriorate if the rate of RSL rise exceeds that of sediment accumulation, causing marshes to drown or cease by erosion (Morris, 2002). Practical problems may also arise for policy makers as rising water encroaches and blurs the line between private property and public beaches, and places infrastructure at risk due to retrogradational land loss, for instance.

A rise in RSL due to the regional factors discussed above can lead to more frequent flooding that needs to be considered in conjunction with eustatic sea-level rise. Several studies have shown that short-lasting storm tides and extreme event flooding have increased in recent years in part due to a regionally elevated RSL (Kemp and Horton, 2013; Sweet et al. 2013; Talke et al., 2014). Pietrafesa et al. (2019) showed that wind and local precipitation play a major role in controlling RSL and flooding following storm events by trapping water within an estuary.

Due to an overall rising RSL, the duration and frequency of high-tide flood events (‘nuisance flooding’, sometimes also called ‘king tides’) has been and will continue increasing all along the East Coast (Sweet et al., 2014; Moftakhari et al., 2015; Ray and

Foster, 2016; Dahl et al., 2017). Sweet et al. (2014) established a linear relationship between lower thresholds for flooding (low land elevations) and a higher yearly frequency of nuisance flooding events for a given gauge. Seasonality of tides has a large impact on nuisance flooding events in the southeast US; higher high tides occur from September to November when seasonal mean sea-level cycles are at their maximum (Sweet et al., 2018). Higher tides also occur from June to July when tidal range increases near the summer solstice and there is a semi-annual peak in the mean sea level cycle (Sweet et al. 2018). In the Southeast Atlantic region high tide flood frequencies have increased by 125% since 2000, a rate faster than all other regions of the U.S. East Coast (Sweet et al., 2018). Moftakhari et al. (2017) examined the economic impact of frequent minor flooding events and showed that these events could cause equal or greater property damage compared to extreme events such as hurricanes or tropical storms. In Charleston, SC nuisance flooding increased from 14 days in 1995 to 38 days in 2015 (Sweet and Marra, 2016). Dahl et al. (2017) showed that from 2001-2015 Charleston had 24 tidal flooding events per year and Springmaid Pier in Myrtle Beach had 3 events per year. A projection using an intermediate sea-level rise projection showed Charleston would increase to 179 flooding events per year and Springmaid would increase to 57 events per year by 2045 (Dahl et al., 2017).

Local Background

RSL rise has previously been studied along the coast of South Carolina in Murrells Inlet, North Inlet and the Santee Delta but data are sparse and data resolution is limited (Brooks et al.,1989; Gayes et al., 1992; Gardner et al., 1992; Gardner and Porter, 2001). These studies focus on the mid-to-late Holocene and suggest a 6 m rise in RSL in the last 7,000 years. Regional trends have been studied from Wilmington to Charleston and are possibly related to local tectonics with RSL in Wilmington influenced by uplift of the Cape

Fear Arch and possible subsidence near Charleston (Gornitz and Seeber, 1989; Van de Plassche, 2014). Brooks et al. (1989) used radiocarbon dating of oyster shell middens in conjunction with the study and dating of peat deposits to construct a RSL curve for the lower coastal plain of South Carolina from 6,000 years ago to 500 years ago. This study suggested that there was a gradual rise from 4,200 years ago to 800 years ago that occurred in a series of 1-2 m fluctuations and since then RSL has risen less than 1 m. Other studies were conducted in South Carolina using stratigraphy and foraminiferal identification (Gayes et al., 1992; Scott et al., 1995b). These studies suggest that a highstand in RSL occurred about 4,200 years ago and was followed by a 2 m decrease in RSL and then a constant rise that persists to the present of 1 cm/10 years. Scott et al., (1995b) suggests that the mechanism of this fluctuation could be caused by cold water along the East Coast of the U.S. and Canada associated with melting ice. Colquhoun and Brooks (1986), Brooks et al. (1989), Gayes et al. (1992) and Scott et al. (1995b) all suggested fluctuations in RSL during the Holocene on a scale of 1-2 m overprinted by a slow and consistent rise in RSL with associate error of about 0.5-1 m (Fig. 3). The effect on local geomorphology of a rising RSL over the last 3,000-4,000 years has been studied in relation to the marshes of North Inlet (Gardner et al., 1992; Gardner and Porter, 2001; Morris et al., 2002). These studies highlight the relationship between RSL rise and salt-marsh formation. As RSL has risen during the last 1,000-2,000 years, the salt marshes of North Inlet transgressed over old Pleistocene beach ridges. Gardner and Porter (2001) suggested that RSL rose slowly and gradually about 0.5 meters over the past 2000 years. Morris et al. (2002) showed that with high sediment availability, marshes such as those around North Inlet could withstand a rate in RSL rise of 1.2 cm/year. These studies give geologic context for current and future

RSL rise. The large error associated with these studies demonstrates the need for higher resolution and more precise data. Higher resolution tide-gauge data exists for Wilmington, NC from 1935 to present and for Charleston, SC from 1901 to present. The tide gauge in Wilmington shows a linear rate of RSL rise of 2.47 ± 0.35 mm/year and in Charleston a linear rate of RSL rise of 3.32 ± 0.19 mm/year. A tide gauge was also installed at Spring-maid Pier in Myrtle Beach in 1957 that shows a linear rate of 3.96 ± 0.52 mm/year. These records all span approximately the same historic period, but variations in the rate of RSL rise can occur from differences in record length, in part due to the increase in rate of RSL rise over the last several decades (Rahmstorf and Vermeer 2011; Talke et al., 2018) While these records are higher resolution than the geologic data from previous studies, there is spatial variation and a significant geographic gap in a long-term record between Wilming-ton and Charleston (approximately 250 km distance between the two tide gauges), further demonstrating the need for more data in the Georgetown/Winyah Bay region.

Geographic Site Description

Winyah Bay, a 65 km^2 partially mixed estuary, located in Georgetown County, South Carolina (Fig. 4) is the third largest estuary on the East Coast of the U.S. with a watershed of about 47,000 km^2 (Allen et al., 2014). Five rivers drain into Winyah Bay (two of which drain into the Pee Dee River before reaching the bay) with the Pee Dee accounting for about 90% of the drainage of this vast watershed (Allen et al., 2014). The Pee Dee River begins in the piedmont of North Carolina and flows through the coastal plain of central North Carolina and northern South Carolina (Patchineelam et al., 1999; Allen et al., 2014) draining a 24,850 km^2 area (Patchineelam et al., 1999). The Waccamaw River, the second largest drainage area (3,910 km^2), drains directly into Winyah Bay along with the Pee Dee and Sampit Rivers. The rivers have a combined freshwater discharge rate of 450-570 m^3/s (Patchineelam et al., 1999; Allen et al., 2014). Patchineelam and Kjerfve (2004) showed that for the year 1996, discharge in the Pee Dee River was above the yearly average from January to April and from August to November with peaks in February (700m^3/s) and September (800 m^3/s). During extreme flooding conditions discharge can be as high as 7,800 m^3 (Allen et al., 2004). Winyah Bay is approximately 30-km long and the funnel-shaped estuary varies in width from 1-7 km (Allen et al., 2014). A main channel runs NW-SE along the central axis and two jetties were constructed in 1904 at the mouth of the bay for navigation purposes. There is a gradient in water surface level over the length of the bay from the ocean to the rivers on the scale of 3-14 mm/km (see *Hydrography Results* Section). The tides in Winyah Bay are semidiurnal with a lag of approximately 2 hours between the mouth and the back part of the bay (Patchineelam et al., 1999). The tidal range is approximately 1.4 m in the lower part of Winyah Bay and approximately 1.2 m at the entrance to the Sampit River (Allen et al., 2014). During seasonal low-flow periods the rivers are tidally influenced on a scale of 100s km and during high-flow periods tides reach 10s km upstream (Allen et al., 2014). The bay is surrounded by 92 km^2 of salt marsh and tidal creeks connect the bay on the northeast side to the neighboring North Inlet Estuary (South Carolina Sea Grant Consortium, 1992; Patchineelam et al., 1999; Allen et al., 2014). Winyah Bay is also surrounded by various industries such as a paper mill, steel mill, coal power plant, and chemical factory. The City of Georgetown and the historic harbor are located in the back of the bay between the Sampit and Pee Dee Rivers.

Meteorological data is collected in North Inlet and can be used to estimate the annual averages for Winyah Bay (NERR, 2020). The average annual precipitation measured in North Inlet over a 30-year period was 125 cm (Allen et al., 2014). The predominant wind direction (data recorded from 1982 to 2004) is from the south and west during the spring and summer, which could push water from the ocean toward the back of Winyah Bay (Allen et al., 2014). Wind direction is evenly distributed in the fall and winter and at an event scale in the spring and summer (Allen et al., 2014).

RESEARCH MOTIVATION, QUESTIONS AND GOALS

Although historic RSL data exists in much of the southeastern United States, this information for the Georgetown/Winyah Bay area is absent. Currently, new access to a historic hand-written tide-gauge record and the installation of a water level logger to collect modern data at the same location, there is an opportunity to study RSL changes at a local scale and for the first time to produce a historic record of RSL for the Winyah Bay/Georgetown region.

There are several mechanisms that play a role in RSL variations in Winyah Bay. The bay is a complex hydrologic system with discharge coming from five rivers of varying sized catchments. Tides, local wind, precipitation, river discharge, and atmospheric pressure are all factors that affect the RSL in Winyah Bay on varying temporal scales from days to years. The morphology and gradient of the bay also play a role in the interaction between river discharge and tides. These processes have not previously been studied in relation to RSL rise in this region so their influence on RSL has not been considered. In this study, the analyses of climatic and atmospheric mechanisms are used to assess their relative contribution to inter-annual variations, both in the Winyah Bay record and between neighboring records of Wilmington and Charleston.

This study reconstructs the RSL history over the past 120 years and is useful for quantifying regional variations with neighboring locations (Wilmington and Charleston). The results will be beneficial for informing urgent coastal management decisions in the future. This research project seeks to answer the following scientific questions:

A. What was the rate of RSL change over the past 150-200 years, and did the rate change over a decadal scale?

B. Which natural forcing mechanisms have control on the RSL in Winyah Bay, and which of these are of short-term influences?

C. Do tide statistics (such as Mean High Water, Mean Low Water and Tidal Range) change between the historic and modern records, and if so did this have an additional effect on RSL rise?

D. How is (nuisance) flood risk changing due to rising RSL or changing tides, and what is to be expected in the near future?

A record of RSL from 1899-1904 was digitized and seasonal and annual variations during that period were analyzed. A rate of change in RSL from 1899 until 2019 was calculated using a combination of the historic dataset and modern data collected at the same location. Modern water-level data throughout Winyah Bay was analyzed to understand what factors control short-lasting, seasonal, inter-annual variations and flooding hazards. This study ultimately compared the RSL record of Winyah Bay to those of Wilmington, NC and Charleston, SC to validate the results as well as understand spatial variability along the coast of the Carolinas.

METHODS

Site Selection

Winyah Bay was chosen as the location of this research because an un-digitized historic tide-gauge record from the Georgetown Lighthouse was discovered, which gives a detailed picture of RSL in Winyah Bay over a five-year period between 1899 and 1904. The City of Georgetown is a low-lying community where RSL rise produces increasing risk for flooding of homes and businesses, thus a local reconstruction on a historic time-scale will be beneficial to its residents. Finally, this area is relatively well-documented with maps and aerial photography, which can be used to determine when certain coastal features developed as well as when they were modified by major engineering projects (such as channel dredging and jetty construction) in the past. The timings of these modifications to the estuary are important to note when considering changes in tidal range and tidal amplitude and can contribute to RSL rise.

Historic and Modern Tide-Gauge Record Data Description

Hand-written tide-gauge data from Georgetown Lighthouse were documented hourly for the years 1899 and 1900 (Fig. 5), and as twice-daily high and low water levels for 1901 to 1904 (Fig. 6). The records were recovered from the U.S. National Archives (courtesy of Dr. Stefan Talke, see Talke and Jay, 2017 for more information), and digitized in excel the fall of 2018 in the Coastal Geosystems Research Lab at CCU (Fig. 7). The records describe an automatic tide gauge with a fixed staff established by the U.S. Engineers in 1898 and was associated with two benchmarks on North Island. A document recovered with the record notes that the tide gauge observations were under the direction of

Reid Whitford, an assistant U.S. Engineer, and were recorded from May 7, 1898 to January 1, 1905; this period overlaps with the construction of the jetties at the entrance to Winyah Bay (Fig. 8). The records were then tabulated by A.G. Reville in July of 1905. A note on one of the documents mentions that in 1925 the benchmark (B.M. 1) on the sill of the lighthouse was recovered but the second benchmark (B.M. 2) was not located (Fig. 9). In October 2018, a trip to North Island led to the re-discovery of B.M.1 (Fig. 10). The modern paint was removed from the sill in order to read the inscription and confirm it was the correct benchmark. A second trip to North Island was undertaken to measure the NAVD88 elevation using a Real Time Kinematic Global Positioning System (RTK-GPS) and a theodolite (survey equipment). The RTK-GPS has a precision of ±2 cm for horizontal measurements and ±1 cm for vertical measurements.

In October 2018, a HOBO water level logger was installed at the original historic lighthouse dock, near where the old tide gauge was collecting data, to measure modern water level at 1-hour intervals (Fig. 11). The logger records water depth as hydrostatic pressure. The NAVD88 elevation of the logger benchmark was also determined with the RTK-GPS. Water level was then calculated based on the measurements of hydrostatic pressure, atmospheric pressure from the National Estuarine Research Reserve (NERR) metrological station in North Inlet (approximately 12 km from the Georgetown Lighthouse), and the vertical distance between logger and GPS-measured benchmark.

Water-depth data from the NERR station in Winyah Bay (Fig 4; NERR, 2020) was used to extend the modern record for two more years. This method is referred to as the "buddy gauge" approach and has been used in other locations to similarly extend the record length of a tide gauge (Hogarth, 2014). This data was acquired from January 1, 2017 to

December 31, 2019 and adjusted to the same elevation as the Georgetown Lighthouse water-level data by plotting the two water-depth data sets together and subtracting the difference between the two. A comparison of the means was then used to verify that the two data sources were approximately the same. The NERR data was subsampled from 15-minute interval data to hourly water-level data to match the resolution of the data from the Georgetown Lighthouse. It was found that although the stations are 13 km apart, differences in tidal amplitude or geometry were not significant.

Water-depth data measured by a second logger at a dock (referred to as Private Dock) at the eastern entrance to the Georgetown inner harbor (Fig. 12) were used to examine differences in water level over the full length of Winyah Bay. These data were also collected by a HOBO water level logger as hydrostatic pressure from which water level was calculated using atmospheric pressure from the metrological station in North Inlet (approximately 9 km from the Private Dock) and adjusted to the NAVD88 elevation. The logger was installed on October 6, 2018 and had three phases of operation: from October 6, 2018 to April 16, 2019, June 21, 2019 to September 21, 2019 and November 2, 2019 to present. Data were not collected between those intervals due to technical issues with the logger.

Sediment Coring and Measurement of ^{210}Pb and ^{137}Cs

A sediment core was collected along a tidal creek at the eastern margin of Mud Bay (Fig. 4) and was used to quantify local sedimentation rates. EMB_01, a 95 cm long push core, was sampled in 5 cm intervals and the sediment collected from each of the 5-cm long samples was mixed into one homogenous sample. The samples were dried, grinded into a fine powder and sent to the USGS Santa Cruz (Dr. Ferdinand Oberle) for ^{210}Pb and ^{137}Cs measurement. ^{210}Pb is a naturally occurring radionuclide of lead that is used for calculation of sedimentation rates and sediment geochronology for deposits less than 100 years old (Appleby and Oldfield, 1978; J. Jouanneau et al., 2002; Kuehl et al., 1996; Nittrouer et al., 1979; Swarzenski et al., 2006). ^{137}Cs is a radionuclide with a half-life of 30 years that is present in the environment due to the testing of nuclear weapons (Ritchie and McHenry, 1990). This radionuclide occurred globally starting around 1950 with maximum fallout peaks occurring in 1959 and 1963 (Hardy, 1971; Ritchie et al., 1973; Ritchie and McHenry, 1990). Linear regression was then used to construct a sedimentation rate for EMB_01.

EMB_01, along with two other cores from the marshes near the South Jetty (Fig. 4), SJM_02 and SJM_03, were scanned using an ITRAX XRF element core scanner in 1 cm intervals at the Lamont-Doherty Earth Observatory. All three cores were sampled at 5 cm intervals for foraminiferal analysis and used as paleo-sea-level indicators (along with chronological control). 16 surface sediment samples were collected during several boat trips to Mud Bay and the elevation of each sample was measured using RTK-GPS. A HOBO water-level logger was installed in the marsh environment and the elevation of the logger was measured using RTK-GPS in order to link the surface sample elevations to MHW, MLW and MSL. The samples were wet-sieved using 63 and 125 μm sieves and foraminifera were picked from the samples and ranged from 5-1,000 tests per sample. The foraminifera tests were counted from 12 of the 16 samples and the organisms are in the processes of being classified into species type for comparison to the foraminiferal species in the three sets of core samples. The geologic RSL reconstruction was not able to be completed during Spring 2019 due to the COVID-19 pandemic which caused loss of access to the samples and lab.

Sea Level Data Description

Yearly average RSL data from the tide gauges at Wilmington, NC (Station ID 8658120; Fig. 11; NOAA Tides & Currents, 2020), Springmaid Pier in Myrtle Beach, SC (Station ID 8661070; Fig. 11; NOAA Tides & Currents, 2020) and Charleston, SC (Station ID 8665530; Fig. 11; NOAA Tides & Currents, 2020) were used to examine regional variations in RSL and land subsidence rates. The tide-gauge records were also used to understand the relationship between precipitation amount/river discharge volume and RSL regionally. The Wilmington, NC tide-gauge data exists from 1935-2019 and the data from Charleston cover the time interval from 1901-2019 with a gap in record from 1903-1922. The Springmaid Pier tide gauge was established in 1957 and there is a gap in data from 1974-1977.

Meteorological Data Description

Meteorological data was acquired from the NERR automated weather station in North Inlet (NIWOLMET; Fig. 4; NERR, 2020), the adjacent estuary to Winyah Bay. Wind speed and direction and barometric pressure were subsampled from 15-minute intervals to 1-hour intervals to match the resolution of the water-level data measured at Georgetown Lighthouse. This data was used to look at the relationship between atmospheric variables and short-term water-level changes inside Winyah Bay. Annual precipitation data from 1895-2019 for South Carolina and the Southeastern region of the U.S. was acquired from the NOAA National Centers for Environmental Information (NOAA NCEI, 2020). This precipitation data was used to compare decadal climatic variability with inter-annual changes in regional RSL. Hourly precipitation for the Pee Dee watershed from 2017-2018 (provided by Dr. Shaowu Bao) was acquired from the NCEP Multi-sensor Stage IV Quantitative Precipitation Estimates Product (Lin and Mitchell, 2005).

This data is mosaicked from regional precipitation radars and gauges produced by the River Forecast Centers (NOAA NWS, 2020).

River Data Description

River gauge-height data was acquired from the USGS website for five stations along the Waccamaw River (Pawleys Island, Bucksport, Socastee, and the cities of Conway and Longs; Fig. 13) and two stations along the Pee Dee River (Pee Dee mouth and Bucksport; Fig. 13). Gauge height is defined as the height of the water in the river above a reference point, this term used by the USGS is the same as what is defined in this study as water level. Daily minimum gauge height was used to avoid extreme events from biasing the data toward higher average water levels for long-term comparisons. Hourly gauge height for 2019 was used for comparison along the Waccamaw River stations that were referenced to a NAVD88 for an average water level. Daily average discharge data from the USGS website was also used to examine the relationship between river flow and tidal range. The discharge of the Pee Dee was collected from the Bucksport USGS Station.

Coastal Sea-Level Data Descriptions

Data was used from the NOAA tidal gauge at Springmaid Pier (Station ID 8661070) in Myrtle Beach, SC to both compare its long-term RSL trend to that in Winyah Bay as well as quantify the seasonal relationship between coastal-offshore water level and water level inside the bay. This tidal station was established in 1954 and the yearly mean sea level was also used to compare the local rate in RSL rise to that of Winyah Bay (approximately 89 km apart), Charleston and Wilmington. The hourly verified (measured water level) and predicted (estimated water level based on tidal predictions) data were used to examine inter-annual variations in coastal water level from 2017-2019.

Tidal Statistics

Yearly Mean Sea Level (MSL), Mean High Water (MHW), Mean Low Water (MLW) and Tidal Range (TR) were calculated for the hourly Georgetown Lighthouse historic and modern records, NERR station data, Private Dock data, the USGS Pee Dee water-level data at the entrance of Winyah Bay, the Waccamaw water-level data from Socastee and Waccamaw water-level data from near Pawleys Island. These statistics were calculated on a yearly basis. The statistics are not identical to the tidal statistics calculated by NOAA (which are normally calculated over a 19-year period) because they were not measured over a 18.6-year nodal cycle.

MSL was calculated as the average of the hourly water level over the course of the year. The change in MSL between the historic and modern records was calculated by subtracting the MSL at the Georgetown Lighthouse in 2019 from the 1899 MSL. The difference between the 2019 MSL and 1899 MSL was divided by 120 years to calculate a linear rate of RSL change between the two records. This calculation was also completed for the MSL records of 1900 and 2019 to calculate error for the rate of RSL rise.

Tidal statistics such as MHW, MLW and TR were calculated using the historic and modern tide gauge records. Each hourly water-level record was then smoothed using a three-point moving average so that minor fluctuations were removed but the tidal signal was not altered. The derivative of the water-level time series was then calculated to find the velocity. A function was used in MATLAB to find the 0-crossing point of the derivative (velocity) which represents a maximum or minimum water level in the original time series. Parameters were set up such that if the derivative crossed 0 multiple times within a six-hour period, the values were not used in order to prevent false high or low water levels.

MHW was then calculated as the average of all high-water levels found during the year and MLW was calculated as the average of all of the low water levels found during the year. TR was calculated by finding the difference between the maximum water level and the next consecutive minimum water level. Events that produced high water levels were not excluded from this calculation, however, the calculated high water and consecutive low water had to be at least 10 hours apart to be included in the calculation. Daily TR was calculated by averaging the two tidal ranges from the twice daily high and low tides together over the year for comparison with other data of daily resolution. Mean Tide Level (MTL) was calculated for the bi-daily records of 1899,1901,1902,1903 and 1904 as average of MHW plus MLW. MTL and MSL were compared to quantify the difference between these two statistics for 1899 which had both bi-daily and hourly data. The difference between MTL and MSL for 1899 was used to estimate MSL for the years where only twice daily high and low data was collected (1901-1904). The yearly MHW, MLW, MSL and TR were used to understand annual tidal statistic changes both temporally from the historic to the modern record as well as spatially throughout Winyah Bay.

Vertical land motion was calculated following a method similar to that used by Zervas et al. (2013) where the rate in eustatic sea-level rise was subtracted from the rate of RSL rise measured at a local tide gauge. Here, yearly average RSL data were used as opposed to the monthly data used by Zervas et al. (2013), thus seasonal and inter-annual variations were not addressed in the calculation presented here as they were in their calculation. The average rate of sea-level from 1900-2013, 1.7 mm/year (Church and White, 2011, 2013), was subtracted from the linear rate of RSL rise calculated for Georgetown

Lighthouse from 1899-2019 and the resulting local vertical land motion rate was compared to the regional data sets presented in Zervas et al. (2013).

Tidal Predictions and Tidal Constituent Extraction

Tidal constituents were calculated for the Georgetown Lighthouse historic and modern records using T-TIDE, a classic harmonic analysis tool available in MATLAB (Pawlowicz et al., 2002). The program calculates tides based on geographic latitude, the provided water-level time series, the start time of the time series, and the overall time interval of data collection. Amplitudes and phases of tidal constituents with a signal to noise ratio greater than 2 were considered significant.

The harmonic analysis was also used to predict past, current, and future tides for the Georgetown Lighthouse records, NERR data, Private Dock data, and USGS Pee Dee data to understand tidal geometry changes across the bay as well as to examine the role of tides in flooding hazard scenarios in Georgetown. Predicted tides were generated using the calculated amplitude, phases and frequencies of the tidal constituents, a date and latitude. The predicted tides were broken down into months and a monthly average was calculated. These values were compared to monthly averaged water-level data to show trends in seasonality and the extent to which the seasonality in tides related to nuisance flooding dynamics.

Local Water Surface Gradient Calculation

Along with variations in land elevation, the gradient of the water surface in Winyah Bay from its northern end down to the ocean entrance is important for quantifying the difference in vulnerability to flooding along the rivers and in the back of the bay (and in the City of Georgetown) compared to the mouth of the bay. The gradient of the water surface along a transect from the lower Waccamaw River and Winyah Bay to the Lighthouse at the mouth of the Bay was calculated using yearly mean water levels of USGS river gauge stations that had a measured NAVD88 elevation (referenced to the elevation by adding the NAVD88 elevation to the water levels) and the distance between two stations. The gradient of the Pee Dee River water surface could not be calculated and compared to the Waccamaw River stations because the river gauges there lacked reference to the NAVD88. The yearly MWL was calculated for the USGS gauge stations near Pawleys Island, Socastee and Bucks Creek (near Longs; Fig. 13). The three data sets were visually inspected with the aim to remove large storm events that skewed the MWL. While these were cleared from the Socastee and Bucks Creek records, the Pawleys Island station is closer to the ocean and thus more affected by tides, which showed that the storm events did not skew the data set at this location. Latitude and longitude coordinates of each river gauge and tide-gauge station were entered into Google Earth and distances between stations were determined using the integrated measure tool. The gradient was then calculated using change in water level during 2019 divided by distance between the two stations closest together.

Long-Term River-Stage Analysis

A yearly average of water-level minima was calculated for the USGS stations on the Waccamaw in Longs, Conway, Socastee, Bucksport, Pawleys Island and the USGS station on the Pee Dee in Bucksport (Fig. 13). The yearly average water levels were plotted and long-term trends were analyzed over the full length of the record to examine the relationship between river water level trends and RSL rise. Linear regression models were created for each of the gauges over two periods, which were selected based on the available record lengths for the USGS stations, to analyze the rate of change in gauge height over time. Coefficients of the linear model were estimated and a T-STATISTIC and the associated P-VALUE were calculated for each coefficient.

Precipitation Analysis

Discharge data is not available for any of the river mouths flowing into Winyah Bay and the data that is available in the closest proximity to the bay spans short time periods. Discharge data was collected from 1994 to 2000 near Pawleys Island (20 km) and 2007 to present in Conway (60 km) for the Waccamaw River. Discharge data has been collected for the Pee Dee River near Bucksport (43 km) from 2007 to present. This lack of data makes it difficult to analyze the relationship between the water flowing into the bay and the effect it has on RSL. There is an established relationship between precipitation, discharge and climatic cycles, therefore, precipitation data was used as a proxy for fluctuations in freshwater flowing into the bay (Hurrell, 1995; Enfield et al., 2001; Zhang et al., 2019). While this approximation does not account for water lost to evaporation or groundwater, it can be used to evaluate seasonal and annual trends in freshwater entering Winyah Bay. The hourly precipitation for the Pee Dee watershed was separated into months and averaged over each month to show seasonal variations in rainfall in the Pee Dee watershed. This data was compared graphically over time with Winyah Bay water-level data, after the tidal signal was removed, to assess coincident seasonal trends between the two data sets and the contribution of the seasonality of precipitation to the cumulative hazard of flood inundation for Georgetown.

Precipitation data on a historic timescale was used to analyze to what extent changes in freshwater input in estuaries like Wilmington, Winyah Bay and Charleston can have on RSL records from this region. The long-term trend in RSL rise was removed from the Charleston and Wilmington RSL records and from the annual precipitation data in order to compare only the inter-annual variations in RSL with inter-annual variations in precipitation. Correlation of detrended SC annual statewide precipitation and detrended Southeastern U.S. regional precipitation data was calculated with the detrended Charleston and Wilmington annual RSL records to quantify the relationship between inter-annual variations in climatic cycles and RSL variations. Correlation coefficients were calculated and then transformed to create a T-STATISTIC and an associated P-VALUE in MATLAB.

Comparison Between the Nearshore Coastal and Winyah Bay Water Levels

Coastal water levels are controlled by oceanic factors such as tides, temperature, salinity, density and the position and intensity of currents. Seasonal and inter-annual variations in oceanic drivers can contribute to flooding hazard in Georgetown. Springmaid Pier water-level data was used to represent water level for the coastal ocean. The tidal signal was removed from both Springmaid Pier and NERR station water-level data sets by subtracting predicted tides (calculated for each year using T-TIDE) from the hourly water-level record for each year. MSL was removed from both the Springmaid Pier record and the NERR station record by calculating an average water level over the year at each station and subtracting that average from the hourly water level record. Monthly averages of the water levels (with tides and the MSL removed) were calculated to analyze seasonal variations and how they compare to those seen in Winyah Bay. The monthly averages of non-tidal water level at Springmaid Pier were compared graphically over time to Winyah Bay non-tidal water-levels for the years 2017, 2018 and 2019 to determine if the seasonality and monthly variation in water level along the coast were consistent with those seen in Winyah Bay. The time component was removed and non-tidal residuals of the water level at the NERR station and Private Dock were plotted against Springmaid Pier non-tidal residual of the water level and compared to a 1:1 ideal relationship line to show differences between the two data sets. Springmaid Pier non-tidal residual water levels were correlated with NERR non-tidal residual water levels and Private Dock non-tidal residual water levels to quantify this relationship. Correlation coefficients were calculated and then transformed to create a T-STATISTIC and an associated P-VALUE.

Nuisance Flooding Analysis

Nuisance flooding for the City of Georgetown was considered to be flooding from tides and a base MSL alone (i.e., without atmospheric pressure, wind or discharge), and therefore was based on the predicted tides (from T-TIDE analysis for the year) and an estimated yearly MSL at the Private Dock. A water-level time series was calculated for 1899-1900, 2017-2019 and a prediction for 2039 to examine past, present and future nuisance flooding occurrence in Georgetown based on the influence of tides and RSL.

The hourly nuisance water-level in Georgetown for the historic record from 1899-1900 was calculated as:

$$\text{Nuisance Water Level}_{\text{historic}} = \text{Tides}_{\text{predicted}} + \text{YMSL}_{\text{Lighthouse}} + \text{Surface Gradient}_{\text{LighthousePD}}$$

where $Tides_{predicted}$ are the predicted hourly tides for each individual year calculated using T-TIDE at the Private Dock station. The Private Dock was selected as the station for analysis (as opposed to NERR or Georgetown Lighthouse) because it is most proximal and therefore most representational for nuisance flooding in the City of Georgetown. The $YMSL_{Lighthouse}$ was calculated as an average water level from each individual year of record at the Georgetown Lighthouse. $Surface\ Gradient_{LighthousePD}$ was estimated using the difference between the 2019 MSL at the Georgetown Lighthouse and the 2019 MSL at the Private Dock. The gradient between these two stations and was assumed to be constant over time. The gradient was accounted for in order to most accurately model the higher base sea level in the back of the bay near the City of Georgetown as opposed to the mouth of the bay.

The hourly nuisance water-level in Georgetown for the modern record from 2017-2019 was calculated as:

$$\text{Nuisance Water Level}_{\text{modern}} = \text{Tides}_{\text{predicted}} + \text{YMSL}_{\text{NERR}} + \text{Surface Gradient}_{\text{NERRPD}}$$

where $Tides_{predicted}$ are predicted hourly tides for each individual year calculated using T-TIDE at the Private Dock station. The $YMSL_{NERR}$ was calculated as an average water level from each individual year of record at the NERR station from 2017-2019. The logger data from the Private dock was not utilized because the record was incomplete and would thus have a biased average for the year. The NERR data also allows for nuisance water level to be modeled over a three-year period as opposed to just one year based on the Private Dock logger. $Surface\ Gradient_{NERRPD}$ was estimated using the difference between the 2019 MSL at the NERR station and the 2019 MSL at the Private Dock. The gradient between these two stations was assumed to be constant over time. The gradient was accounted for in order to most accurately model the higher base sea level in the back of the bay near the City of Georgetown as opposed to the mouth of the bay.

Nuisance flooding was then predicted in 20 years for the year 2039. A 20-year time interval was chosen as the prediction because it is a tangible future for many residents of Georgetown (generally property mortgages are for about this period of time as well) and this period also limits the variation in RSL due to the 18.6-year nodal cycle. The hourly nuisance water-level in Georgetown for the future record for 2039 was calculated as:

$$\text{Nuisance Water Level}_{\text{future}} = \text{Tides}_{\text{predicted}} + \text{MSL}_{\text{estimated2019}} + \text{RSLR}_{2039}$$

where $Tides_{predicted}$ are predicted hourly tides for the year 2039 calculated using T-TIDE at the Private Dock station. $MSL_{estimated2019}$ is calculated as $YMSL_{NERR}$ (for 2019) + *Surface*

$Gradient_{NERRPD}$. *$RSLR_{2039}$* was estimated using the annual rate of current global sea-level rise of 3.3 mm/year (NASA, 2020) and adding the calculated vertical land motion. This rate in RSL rise was kept constant and multiplied by 20 years, which probably underestimates the accelerating nature of current and future RSL rise based on simulations (Hamlington et al., 2020; Horton et al., 2020).

A threshold for flooding on land needed to be established so that the predicted water level over a specified land elevation would be considered an occurrence of nuisance flooding. Land elevation levels for nuisance flooding were established using RTK-GPS measurements of locations in Georgetown known to frequently inundate: 901 Front Street (0.93 m elevation NAVD88; 0.27 m above MHHW) and the corner of Front Street and Greenwich Drive (0.55 m elevation NAVD88; 0.11m below MHHW). MHHW from the Waccamaw NOAA tidal station was used as a third nuisance flooding level (0.66 m NAVD88) as a relative elevation reference to compare the results to other nuisance flooding studies (Fig. 12).

An occurrence of nuisance flooding at 901 Front Street was defined as:

Modeled Nuisance Water Level > 0.93 m

An occurrence of nuisance flooding at Front Street and Greenwich Drive was defined as:

Modeled Nuisance Water Level > 0.55 m

An occurrence of nuisance flooding at MHHW level was defined as:

Modeled Nuisance Water Level > 0.66 m

Where *Modeled Nuisance Water Level* is the calculated water-level time series for the 1899-1900, 2017-2019 and 2039 records representing water level fluctuations due to the influence of tidal oscillations and RSL. From this model, durations of nuisance flooding (in hours and days) for each year were calculated and compared to existing literature.

Flooding Analysis

Flooding in Georgetown was considered to be the cumulative inundation hazard resulting from the temporary 'positive' stacking of several of the forcing mechanisms described above at the same time. The same 3 elevation levels were used as flooding thresholds around the City of Georgetown: 901 Front Street (0.93 m elevation NAVD88; 0.27 m above MHHW), the corner of Front Street and Greenwich Drive (0.55 m elevation NAVD88; 0.11m below MHHW) and MHHW from the Waccamaw NOAA tidal station (0.66 m elevation NAVD88). Historic, modern and future modeled flooding time series were constructed for Georgetown using the predicted tides and mean sea level and non-tidal residuals (representing drivers of sea level such as discharge events, fluctuations in atmospheric pressure and wind). The hourly flooding water-level in Georgetown for the historic record for 1899-1900 was calculated as:

$$\text{Modeled Flooding Water Level}_{\text{Historic}} = \text{Tides}_{\text{predicted}} + \text{Surface Gradient}_{\text{LighthousePD}} + \text{NTR}_{\text{Lighthouse}}$$

where $Tides_{predicted}$ are the predicted hourly tides for each individual year calculated using T-TIDE at the Private Dock station. The Private Dock was selected as the station for analysis (as opposed to NERR or Georgetown Lighthouse) because it is most proximal and therefore most representational for flooding in the City of Georgetown. $Surface\ Gradient_{LighthousePD}$ was estimated using the difference between the 2019 MSL at the Georgetown Lighthouse and the 2019 MSL at the Private Dock. The gradient between these two stations and was assumed to be constant over time. The gradient was accounted for in order to most accurately model the higher base sea level in the back of the bay near the City of Georgetown as opposed to the mouth of the bay. $NTR_{Lighthouse}$ is calculated by taking the original tide gauge record from the Georgetown Lighthouse and subtracting the predicted tides at the lighthouse for the year calculated using T-TIDE. These non-tidal residuals are used to account for high water levels due to riverine flooding and atmospheric effects on water level. MSL at the lighthouse was not removed from $NTR_{Lighthouse}$ and therefore is accounted for with the use of this term in the Modeled Flooding Water Level equation.

The hourly flooding water-level in Georgetown for the modern record for 2017-2019 was calculated as:

$$\text{Modeled Flooding Water Level}_{\text{Modern}} = \text{Tides}_{\text{predicted}} + \text{Surface Gradient}_{\text{NERRPD}} + \text{NTR}_{\text{NERR}}$$

where $Tides_{predicted}$ are the predicted hourly tides for each individual year calculated using T-TIDE at the Private Dock station. $Surface\ Gradient_{NERRPD}$ was estimated using the difference between the 2019 MSL at the NERR station and the 2019 MSL at the Private Dock. NTR_{NERR} is calculated by taking the original tide gauge record from the NERR station and subtracting the predicted tides at the NERR station for the year calculated using T-TIDE. The NERR station non-tidal water level residuals were used as opposed to the private dock logger data because the record at the NERR station was complete for the entire period from 2017-2019 and therefore better suited for analysis of seasonal and interannual variations in flooding.

The hourly nuisance water-level in Georgetown for the future record for 2039 was calculated as:

$$\text{Modeled Flooding Water Level}_{Future} = \text{Tides}_{predicted} + \text{Surface Gradient}_{NERRPD} + \text{NTR}_{NERR2019} + \text{RSLR}_{2040}$$

where $Tides_{predicted}$ are the predicted hourly tides for the year 2039 calculated using T-TIDE at the Private Dock station. $Surface\ Gradient_{NERRPD}$ was estimated using the difference between the 2019 MSL at the NERR station and the 2019 MSL at the Private Dock and was assumed to be constant over time. NTR_{NERR} is calculated by taking the original tide gauge record from the NERR station in 2019 and subtracting the predicted tides at the NERR station for the year calculated using T-TIDE. For future flooding, the non-tidal water-level residuals of 2019 were considered to be a "normal" year of observation in terms of seasonality, high discharge events, atmospheric fluctuations (wind and pressure), oceanic variations (such as currents) and climatic forcing (precipitation and discharge cycles). $RSLR_{2039}$ was calculated using the current global rate of 3.3 mm/year (NASA, 2020) and the calculated vertical land subsidence rate. The rate was kept constant and multiplied by 20 to estimate a projected RSL in 20 years.

The occurrence of flooding at each threshold elevation on land (0.55 m, 0.66 m and 0.93 m) was modeled as times when the generated water levels (water level residuals and MSL) were greater than the threshold land elevations.

An occurrence of flooding at 901 Front Street was defined as:

Modeled Flooding Water Level > 0.93 m

An occurrence of flooding at Front Street and Greenwich Drive was defined as:

Modeled Flooding Water Level > 0.55 m

An occurrence of flooding at MHHW level was defined as:

Modeled Flooding Water Level > 0.66 m

Flooding over the three elevation thresholds was calculated for the historic, modern and future records and durations of flooding for each year were calculated and compared for all years of analysis.

Major Storm Event Analysis

Storm events in the historic Georgetown Lighthouse and NERR station records were calculated by taking the measured water level and subtracting predicted tides and yearly mean sea level. Major storm events were considered events greater than 2 standard deviations of the storm record (Zhang et al., 2000). These major storm events were counted each year and compared between the historic and modern records in terms of size and number. This analysis was conducted to further understand how flood inundation hazard has changed in Georgetown based on the number and size of large storm events.

RESULTS AND DISCUSSION

A. RSL Rise in Winyah Bay/Georgetown – Results

Calculating the vertical difference between the yearly MSL from 1899 and the modern yearly MSL from 2019, both adjusted to the same vertical datum, determined the *average long-term mean RSL rose 55 cm over the past 120 years* (Tab. 1, Fig. 14). A hypothetical *long-term linear rate* in RSL rise at the Georgetown Lighthouse was *4.6 mm/year*.

The range of inter-annual variability of MHW over the six-year historic record was 0.15 m, and the range in MHW over the three-year modern record from the NERR station was similar at 0.12 m. The inter-annual range in MLW over the six-year historic record was 0.07 m, and 0.17 m over the three-year modern record from the modern station (Tab. 1). The historic records of 1899 included both hourly and bi-daily measurements allowing for the comparison of MSL and MTL. The difference between these two statistics in 1899 was 0.05 m. The difference between MSL and MTL for 1899 was used to estimate MSL for 1901-1904 (Tab. 1).

The rate of *vertical land motion* calculated using the historic and modern tide-gauge records and subtracting the 20th century average eustatic rate in sea-level rise (Church and White, 2011) was *-2.9 mm/year* (Tab. 2). The rate calculated is a negative value, demonstrating land subsidence.

Measurements of ^{210}Pb and ^{137}Cs profiles in sediment Core EMB_01 were used to examine local sedimentation rates in the marshes around Winyah Bay to quantify the balance between RSL rise and marsh accretion in Winyah Bay (Fig. 15). Samples 1-5 representing depths 5-10 cm to 25-30 cm show a linear trend and their associated ages are 2010, 2000, 1987, 1975 and 1970. Below 30 cm the values of excess ^{210}Pb are too low to be used for dating and are most likely the background level. This observation suggests that approximately 30 cm of sediment was deposited at this location since 1970, i.e. over the past 50 years. Linear regression of the results for the first four samples of the core showed a linear accretion rate of approximately 0.7 cm/year. These results are consistent with the ^{137}Cs measurement, which shows a small peak in Sample 5, possibly indicating the 1964 spike in ^{137}Cs (Fig. 16).

Precision errors in the calculation of an overall RSL rise have been considered to potentially result from several sources. The RTK-GPS has an average vertical precision of 1 cm as taken from the manufacturing manual. The error in the theodolite used in the measurement of the historic benchmark was 2 cm from field-based validation. The validation of the theodolite measurement was calculated by surveying the transect from an established RTK-GPS measured point to the benchmark on the Georgetown Lighthouse twice and then subtracting the two measurements. The deviation associated with the HOBO water-level logger was 0.6 cm as stated in the manufacturing manual (Onset, 2020). The precision in the atmospheric pressure measurement, used for the conversion from measured underwater-pressure data to water level, was 1 cm according to the source of data acquisition (NERR, 2020). Thus, the overall precision of the modern RSL measurement is ± 2.6 cm or about 5% of the measurement. The precision range in the historic data includes the 1 cm average precision from the RTK-GPS elevation measurement and the 2 cm precision for the theodolite-based validation of the historic benchmark elevation. Leveling error for the historic benchmark is difficult to quantify without documentation of the initial survey, however, leveling error has been estimated to be on the scale of ± 1 cm (Talke et al., 2020). There is error associated with the difference in location of the modern and historic tide gauges; the dock where the historic logger was installed is no longer present at the Georgetown Lighthouse so the modern logger is located approximately 100 m south of where the previous dock stood. A gradient in water level between these two locations is most likely negligible. Finally, precision was estimated for the historic record by calculating a difference in the rate of RSL rise between 1899-2019 and 1900-2019, which led to a range in precision of ± 0.004 cm. Therefore, the measurable precision for the historic record is ± 4.004 cm. The overall error from the RSL measurement was propagated through to the rate of sea level rise using a graphical approach, where the maximum error on the modern RSL measurement (3 cm + 2.6 cm) and the maximum error on the historic RSL measurement (-53 cm + - 4 cm) were used to calculate a rate of RSL rise over the 120 years. The difference, ± 0.6 mm, between the maximum error rate and the calculated rate was used to represent the error range in the rate of RSL calculated in this study.

RSL Rise in Winyah Bay/Georgetown – Discussion

The calculated rate of RSL rise presented in this study quantifies local RSL change for the first time in this geographic region on a historic timescale. The rate in RSL rise that was calculated here (4.6 ± 0.6 mm/year) is greater than that in the Charleston estuary (3.32 ± 0.19 mm/year), and the Wilmington/Cape Fear lower river (2.47 ± 0.35 mm/year) over the same approximate time period. The rate is also higher than the rate of ocean-facing Springmaid Pier in Myrtle Beach (3.96 ± 0.52 mm/year), although comparison is difficult with the difference in record length between the two stations (Fig. 17).

Similarly, the extracted linear average rate in subsidence of -2.9 mm/year for the new record is greater than the estimated subsidence rates for Charleston, SC (-1.24 ± 0.07 mm/year), Wilmington SC (-0.43 ± 0.22 mm/year) but comparable to that calculated for Springmaid Pier (-2.34 ± 0.63 mm/year; Tab. 2; Zervas et al. 2013). Analysis of GPS stations compiled by the Nevada Geodetic Laboratory (NGL) have measured subsidence rates over the past 5-10 years that range from -2.24 ± 1.17 to -2.88 ± 0.83 mm/year (Blewitt et al., 2018).

On a century scale, there are several controls on vertical land motion that could cause regional differences between RSL records of Wilmington, Winyah Bay and Charleston. GIA can explain regional differences in subsidence between the Southeastern Atlantic, Mid-Atlantic and Northern Atlantic Coast but is likely not a large factor in explaining differences within the NC-SC region greater than a few tenths of a mm/year (Engelhart et al. 2009; Van De Plassche et al. 2014; Kemp, 2017). GIA is estimated to contribute 0.70 mm/year to RSL rise in Charleston (Snay et al., 2007; Love et al., 2016). The Cape Fear Arch, a structural feature with a crest near Wilmington, NC, is estimated to uplift at a rate of 0.24 mm/year which could explain some of the difference between the tide gauge there, Springmaid and Charleston (Van De Plassche et al. 2014). Tectonics could also influence vertical land motion and regional variations between Savannah, Charleston and Georgetown County but these processes are not well understood and the rate at which this would impact RSL is not yet constrained (Colquhoun and Brooks, 1987; Gornitz and Seeber 1989; Rhea, 1989; Marple and Talwani, 1993). Faults have been studied around Charleston and deep geologic structures, such as those which caused the 1886 earthquake, have been suggested to cause local vertical land motion and thus would cause differential land motion between Charleston and regions to the north and south (Gornitz and Seeber 1989; Rhea, 1989; Marple and Talwani, 1993).

Groundwater extraction leading to vertical aquifer contraction is one possible cause of land lowering. 79% of the groundwater used in Georgetown County comes from the Crouch Branch of the Black Creek aquifer (Berezowska and Monroe, 2017). A potentiometric map for the Black Creek aquifer, specifically the Crouch Branch, reveals a cone of depression around the area of Georgetown which extends out to the bay (Fig. 18; Hockensmith, et al. 2013b). Observations from water levels in wells in this branch of the aquifer show a decline of about 30.5 m from 1970 to 2016 with an average rate of about 58 cm/year (Berezowska and Monroe, 2017). Karegar et al. (2016) attributed 50% of modern land subsidence in the region from Virginia to South Carolina to groundwater extraction and resulting aquifer compaction based on groundwater level data and GPS measurements. If 50% of subsidence in the Georgetown/Winyah Bay area is due to groundwater extraction, this effect would contribute 1.45 mm/year to the rate of land subsidence. Aucott and Speiran (1987) and Harder et al. (2012) showed that the Black Creek aquifer, which is used by the Georgetown and Myrtle Beach communities, was more significantly affected by groundwater pumping than the aquifers used by Charleston. The groundwater levels at well GEO-0077 in Georgetown County (Fig. 18) have declined by 30.5 m (100 ft) from 1975-2016 and the levels at well HOR-0309 in Horry County have dropped 33.5 m (110 ft) during the period of 1973-2017 (Fig. 18; Berezowska and Monroe, 2017). In Charleston, the Floridan aquifer well CHN-0044 (Fig. 19; Berezowska and Monroe, 2017) decreased by 7.93 m (26 ft) over the period 1981-2013. The Middendorf aquifer well CHN-14 in Charleston County decreased by 12 m (40 ft) between 1991-2011 (Hockensmith, 2012; Harder et al., 2012).

These water-level declines equate to linear rates of groundwater height decline in Horry and Georgetown Counties (0.73 m/year) almost twice as large as those in Charleston County (0.43 m/year) and could explain the 53% difference in the calculated subsidence rates between Winyah Bay and Charleston and the 47% difference between Springmaid Pier and Charleston. To exactly quantify the extent groundwater extraction contributes to land lowering in Georgetown requires more specific investigations in the future.

If the annual rate of subsidence in Winyah Bay due to GIA and groundwater extraction are subtracted from the calculated long-term annual rate of vertical land motion there still remains 0.76 mm/year of unexplained vertical land motion (Fig. 20). Karegar et al. (2016) showed a weak correlation between local GPS measured subsidence and local coastal plain thickness in the southern Atlantic Coast Region. This relationship may show that while not being a major driver of local subsidence, sediment loading could be a small factor in vertical land motion in the region. Miller et al. (2013) showed compaction of Holocene aged deposits in coastal New Jersey occurring at a rate of about 0.3-0.6 mm/year and thermoflexural subsidence and compaction of pre-Holocene deposits along the coastal plain at a rate of 0.1 mm/year. Due to the soft sediments along the coast of South Carolina, the compaction of Holocene-aged deposits is a more probable control on subsidence in the Winyah Bay region.

Due to the lack of data in Winyah Bay in between the 6-year historic record and the 3-year modern record, the tide gauges in the surrounding regions were used to investigate decadal-scale trends. Some decadal-scale trends noted in the Charleston, Wilmington and Springmaid tide-gauge records match with variations in the rate of eustatic sea-level rise shown with the Hay (2015) curve. Eustatic sea-level rose at a rate of 1.37 mm/year from

1900-1950. This eustatic sea-level record shows a slowing down of the rate to 0.37 mm/year from about 1950-1968, which corresponds with general trends seen in the Wilmington and Charleston tide-gauge records (Fig. 17). In contrast, the Hay curve shows an increased rate from 1993-2010 to 2.74 mm/year, which is not consistent in at the gauges in Charleston (1.1 mm/year), Wilmington (-0.5 mm/year) and Springmaid Pier (0.08 mm/year).

In order to investigate how rates in RSL rise may differ from eustatic sea level on a decadal scale, the rates in RSL rise in Charleston, Myrtle Beach (Springmaid Pier) and Wilmington were analyzed from 1993-2013 and from 2009-2019 (Tab. 3). During the period from 1993-2013 all three tide gauges showed a lower or similar rate in RSL rise to eustatic rates in sea-level rise (3.0 mm/year in Charleston, 1.7 mm/year in Myrtle Beach and 0.4 mm/year in Wilmington) despite global sea-level rise occurring at a faster rate compared to the beginning of the 1900s. This 20-year period from 1993-2013 was very different from the period 2009-2019 where RSL rise at all three of these stations was much faster than that of global sea-level rise (14 mm/year in Charleston, 9 mm/year in Myrtle Beach (Springmaid Pier) and 15 mm/year in Wilmington).

To understand these dynamics, these RSL rise rates were broken down further by examining to what extent global sea-level rise, subsidence rates and inter-annual variability in ‘oceanic’ components (such as atmospheric pressure, water salinity, water temperature, wind field, and coastal ocean currents) contribute to the locally differing rates of RSL rise. GPS measurements from the Nevada Geodetic Laboratory (NGL) were used to quantify modern rates of subsidence in Wilmington (-1.5 mm/year), Myrtle Beach (-2.9 mm/year) and Charleston (-1.4 mm/year). These rates were assumed to be constant over both time periods (Tab. 3; Blewitt et al., 2018). Global sea-level rise rates were calculated using Church and White (2011) for the 1993-2013 rates and satellite data from NASA for the 2009-2019 rates. Oceanic variability trends during 1993-2013 and 2009-2019 were quantified using NOAA's inter-annual variation of monthly RSL since 1990, where the average seasonal cycle and linear sea-level trend have been removed (NOAA Tides and Currents, 2020). All three tide gauges showed a negative trend in the oceanic inter-annual variability during the 1993-2013 period (-1.3 mm/year in Charleston, -2.3 mm/year in Myrtle Beach and -2.2 mm/year in Wilmington; Tab. 3). During the period 2009-2019 when all three tide gauges showed a rate of RSL rise faster (14 mm/year in Charleston, 9.2 mm/year in Myrtle Beach and 15.6 mm/year in Wilmington) than the rate of global sea-level rise (3.3 mm/year) the trend in oceanic variability was positive and large (9.8 mm/year in Charleston, 5.2 mm/year in Myrtle Beach and 9.3 mm/year in Wilmington). These data show that changes in ocean currents (Ezer et al., 2013), salinity related to fluvial freshwater discharge and surface runoff (Piecuch et al. 2018), temperature, atmospheric pressure and local wind may play a significant role in changing RSL on a decadal scale (NOAA Tides and Currents, 2020; Fig. 21). This analysis looks at changes in annual MSL and short-term inter-annual trends in the components of RSL rise. The relative contributions of each component (oceanic variability, global sea level rise, etc.) to the overall trend in RSL rise on a decadal scale come with a large statistical uncertainty due to noise in the trend in the individual components associated with inter-annual variability in the data (Tab. 4). While analysis of long-term trends in sea-level rise has less statistical uncertainty because the trend in each component is much larger than the inter-annual noise, the impact of processes which may have a large effect on the rate of sea-level rise on a decadal scale become less obvious.

Higher MSL has a large role in the increase in flooding in low-lying areas by raising the base water-levels (see Section C*, Nuisance Flooding*). The analysis conducted here shows that on a decadal scale, variations in oceanic factors (such as changes in water density and trends in ocean currents) can cause RSL to vary on a scale of 10s of mm/year.

After exploring how RSL rise rates vary on a decadal scale and can be influenced by factors other than global sea-level rise, this analysis can be used to estimate the linear rate of RSL rise for Winyah Bay in a modern context. There has been an increase in eustatic sea-level rise from the 1.7 mm/year 20th century historic rate to 3.3 mm/year (from NASA satellite data 1993-2019) in recent years. If the modern rate of eustatic sea level is added to the calculated subsidence rate for Winyah Bay of -2.9 mm/year, a modern rate of RSL rise would be approximately 6.21 mm/year. If the oceanic variability trend from Spring-maid Pier (nearest data to Winyah Bay) from 2009-2019 is added to the modern RSL rise rate calculated for Winyah Bay, the current rate could be as high as 11.4 mm/year (1.14 cm/year) from a 'stacking' of eustatic sea level, subsidence and oceanic variability.

The excess ^{210}Pb profile shows that the sediment accretion rate in the marshes around Winyah Bay of 0.7 cm/year is high enough for the marshes to keep up with the current long-term linear rate of RSL rise of 4.6 mm/year. Artificial compaction should be considered when analyzing the results for EMB_01 however, the sedimentation rate calcu-lated here is close to rates obtained from the nearby marshes of North Inlet. Sharma et al. (1987) took several sediment cores and measured accretion rates ranging from 1.4 to 4.5 mm/year. Marsh plants control the elevation of the surface by accumulating organic sedi-ments as they grow and trapping inorganic sediment in their root network which explains the high accretion potential (Morris et al., 2002). Morris et al. (2002) showed that marsh plants have optimal rates of RSL rise with which they thrive (based on primary production, sediment trapping and erosion rates) and predicted that due to high sedimentation rates in North Inlet, coastal wetlands under these conditions could remain stable with rates of RSL rise as high as 1.2 cm/year. Considering the long-term linear rate of RSL rise for Winyah Bay of 4.6 mm/year, the marshes are far from instability, however, if the modern estimated rate of 1.14 cm/year is considered the marshes could face the possibility of sediment erosion or drowning if the current trends persist.

B. Hydrography of Winyah Bay– Results

The surface water-level gradient of Winyah Bay was analyzed by calculating change in MHW, MSL and Tidal Range between the Private Dock gauge and the Georgetown Lighthouse gauge for 2019 (Tab. 5). The gradient of the water level from the ocean to the rivers has implications for quantifying flood inundation hazard in the City of Georgetown. There was an increase in MSL of 0.25 m and in MHW of 0.17 m from the Lighthouse to the Private Dock. The tidal range decreases over the same distance by 0.14 m. The decrease in tidal range and increase in MWL and MHW continued in the rivers that flow into Winyah Bay as well. There was an increase in MSL of 0.1 m from Pawleys Island to Socastee in the Waccamaw River and a decrease in tidal range of 0.47 m. The steepest gradients occurred from Longs, SC to Socastee, SC (73 mm/km) and then from the Private Dock to the Lighthouse (14 mm/km) (Tab. 6). Although the gradient is not linear from the ocean to the rivers inland, there are general trends over the course of the coastal plain: the gradient is larger inland at Longs (73 mm/km) and lower near the mouths of the river at Socastee (4 mm/km) and Pawleys Island (3 mm/km).

Harmonic analysis of tidal constituents showed that tidal amplitudes changed on a scale of 0.1-1 cm between the historic and modern tide-gauge records (Tab. A, Appendix). No changes in tidal amplitude between the historic and modern records were greater than those seen by an inter-annual comparison. This negligible change in tidal amplitude means that the tides can be considered stationary between the historic and modern record. On an annual scale, the monthly averages of predicted tide heights were analyzed to understand which times of the year tides may be the most important for tide-related flood hazard in Georgetown. First, the predicted tides from Georgetown Lighthouse were compared to the

NOAA predicted tides for the same location (Station ID 8662747; NOAA Tides & Currents, 2020) to verify the accuracy of the tide predictions modeled with T-TIDE. They were shown to be similar in terms of timing and amplitude of predicted tides (Fig. 22). The monthly average predicted tides for Georgetown Lighthouse exhibited a seasonal trend with higher astronomic tide levels in March to May and September to November. The monthly average tide levels were lower in December to February and June to August (Fig. 23). This seasonal cycle occurred in both the historic and modern records and affects the water level in northern Winyah Bay on a similar scale of ± 0.2 m. The seasonal variations of the tides were noticeable in the historic and modern water-level records from Georgetown Lighthouse with higher water levels at the Lighthouse during March to May and September to November. Other processes such as discharge, precipitation and ocean currents contribute to the variation in water level beyond those trends seen in the predicted tides and become observable when the tidal signal is removed from the water-level record.

Discharge and precipitation are two processes that influence water levels in Winyah Bay also on inter-annual to decadal timescales. Linear regression was used to analyze Waccamaw River water level in order to quantify any long-term trends in water level that may have occurred. The water level trends at the gauges were analyzed over two periods, 2001-2019 and 2005-2019, because several of the gauges were installed between 2001 and 2005. All of the Waccamaw gauges except the one in Longs, SC show a significant increase in water level ranging from 2.47-6.89 mm/year over the two periods of analysis (Tab. 7). The water level at the Pee Dee gauge in Bucksport, SC was analyzed over the same periods and showed no significant long-term trend.

Inter-annual changes in water level were compared graphically for the Pee Dee and Waccamaw rivers. The Pee Dee River gauge data showed no discernable inter-annual trends in either of the gauges analyzed. In the Waccamaw gauges, the period from 1990-2001 was characterized by declining water levels at the gauges in Longs, Conway and Socastee. In Longs the water level decreased about 1 m from 1990-2001 and in Conway water level decreased about 0.5 m. This period was followed by an interval of stagnation in water level from approximately 2002-2007 at all gauges along the Waccamaw River. During this period, greater magnitude fluctuations in water levels were seen in the Longs and Conway gauges (about 0.5 - 1 m) and smaller magnitude fluctuations in water level occurred at Socastee and Pawleys Island (about 0.2 m). From 2007 to 2019 there was a period of increase in water level at all five gauges along the Waccamaw River on a scale of 0.2 - 0.5 m (Fig. 24).

The detrended annual RSL records of Wilmington and Charleston were visually compared to the detrended annual precipitation for South Carolina, North Carolina and the Southeastern region of the United States from 1899 to 2019 to further analyze the relationship between climatic factors and inter-annual sea-level variability. Higher RSLs observed at Charleston, Wilmington and Winyah Bay on the scale of 0.1 m over the past two years corresponded with an increase in precipitation by approximately 30 mm (Fig. 25). Both RSL and precipitation have been generally increasing since about 2011. There was a small decrease in the amount of precipitation in 2016-2017 that corresponded with a lower yearly MSL at both Charleston and Wilmington (Fig. 25). Historically, peaks in annual precipitation corresponded with peaks in annual MSL, such as in 1948, 1960 and 1973 (Fig. 25). Correlation coefficients and associated p-values were calculated to quantitatively examine the relationship between regional precipitation and RSL at the Charleston and Wilmington gauges. The correlation coefficient for the relationship between southeastern U.S. precipitation and Charleston yearly mean sea level was 0.39 (P-VALUE 0.0002) and the correlation coefficient between southeastern U.S. precipitation and Wilmington was 0.54 (P-VALUE 0.0000). The correlation between these variables at both locations indicates a relationship between inter-annual changes in precipitation and inter-annual changes in RSL (Tab. 8).

On an annual scale, precipitation in the Pee Dee watershed during 2017-2018 was highest from March to October with large hurricane-related rainfall events occurring in September and October (Fig. 26). The monthly mean water level in Winyah Bay at the NERR station with predicted tides removed was compared to the monthly averages of precipitation in the Pee Dee River watershed in order to understand the influence of local precipitation on flood inundation hazard for Georgetown. In 2017, the non-tidal residual water-level at the NERR station in Winyah Bay increased from March to May, at the same time as precipitation in the Pee Dee watershed. There was an increase in precipitation from July to September while a slight decrease in the Winyah Bay non-tidal residual water level occurred. In 2018, there was an increase in precipitation in the Pee Dee watershed during January to March, June to July and August to September. The non-tidal residual water-level in Winyah Bay exhibited similar trends in June to July and August to September except the water level continued to rise after the precipitation peak in September.

Discharge dampened the tidal range during high-flow events from 2017-2019 both in Georgetown Harbor (USGS Pee Dee entrance station) and at the NERR gauge (Fig. 27). The relationship between discharge and tidal range was the same at both the Lighthouse and the USGS Pee Dee entrance stations. Occasionally, during high discharge events a decrease in tidal range occurred, i.e. during events in May and July of 2019 at both stations (Fig. 27). During the high discharge event in September of 2019 (Hurricane Dorian) there was a decrease in tidal range that occurred at both stations before the increase in water discharge. Tidal range then increased concurrently with the increased water discharge. The relationship between discharge and tidal range that occurred during Hurricane Dorian is unique compared to other high discharge events where an increase in discharge was coincident with a decrease in tidal range. The relationship between discharge and tidal range was also examined by plotting the two variables against each other to determine if there is a linear relationship that could quantify the dependence of tidal range on discharge. Although a clear linear relationship is not exhibited, when months and seasons are accounted for there are some periods where a linear relationship between discharge and tidal range may occur (during January and March 2019) (Fig. 28). There were several instances where a linear relationship existed between a few points, indicating that this relationship may be clearer at an event scale. The seasonal patterns were not consistent from year to year.

Coastal RSL measured at Springmaid Pier exhibited a seasonal trend with higher water levels in February to April and August to October and lower water levels in November to January and May to July. Graphical comparison of weekly averages of Springmaid Pier and NERR non-tidal water-level revealed that coastal water levels were generally higher than water levels inside the bay from January to June but the inter-weekly variations in water level between the two locations throughout each year were the same (Fig. 29). Correlation of non-tidal Springmaid water level and non-tidal NERR water level resulted in a significant relationship between coastal water level and water level in Winyah Bay (Tab. 9). The same relationship exists between non-tidal Springmaid water level and non-tidal Private Dock water level (Tab. 9). NERR non-tidal water-level residuals and Springmaid non-tidal water-level residuals exhibited a linear relationship between the coastal ocean and the distal part of Winyah Bay when plotted against each other (Fig. 30). Private Dock non-tidal residual water levels also exhibited a linear relationship with Springmaid non-tidal residual water-levels (Fig. 31). Although the relationship was linear the slope of the line was steep, further demonstrating the existence of higher water levels at the Private Dock compared to the coastal ocean.

Hydrography of Winyah Bay– Discussion

The water surface gradient in Winyah Bay increases from Georgetown Lighthouse to the Private Dock indicating a naturally a higher base water-level at the City of Georgetown compared to the mouth of Winyah Bay. A higher base RSL creates a lower threshold for high tides or discharge to cause flooding events. The water-level gradient of 73 mm/km between Longs and Socastee is the steepest interval found in the analysis. The gauge at Longs may also show a higher mean water-level because this location is significantly upstream, outside of tidal influence. The water-level gradient decreases between Socastee and Pawleys Island and between Pawleys Island and the Private Dock (Tab. 6). The lower gradients likely occur due surface elevation and gently sloping geomorphology as the rivers approach the bay. Also, in the northernmost part of Winyah Bay as the streams significantly widen, the water surface gradient may decrease. The surface water-level gradient increases again from the Private Dock to the Lighthouse, where the entrance to Winyah Bay is wide and unobstructed and water flow from tides can have their greatest influence.

The lower tidal range at the Private Dock compared to NERR station and Georgetown Lighthouse along with the lower tidal ranges occurring during high flow events demonstrates that theoretical tidal amplification or a 'funneling effect' in the narrowing bay head area is not a significant mechanism in controlling flood inundation in Georgetown. Generally, in funnel shaped bays, tides may amplify and increase from the ocean to the back of the bay (Talke and Jay, 2020), which would greatly increase flooding hazard for the City of Georgetown. Here, it was shown that the shape of the bay, along with the generally shallow depth, does not cause amplification of the tides, possibly due to the influence of the rivers discharging a significant amount of water into the bay and the effect of friction (Friedrichs and Aubrey, 1994). There is a balance between the frictional force created between the river discharge and the incoming tides that may slightly outweigh the funneling effect (Jay, 1991). The approximate volume of Winyah Bay based on average depth is 2.6×10^8 m^3 and the average combined discharge of the five rivers is 570 m^3/s (Patchineelam et al., 1999; Allen et al., 2014). According to these estimates, about 20% of the water in the bay is replaced by freshwater discharge every day, further indicating the significance of the discharge from the rivers.

Tidal amplitude at the Georgetown Lighthouse did not change significantly (on a scale of 0.1 cm) from the historic to the modern record. The lack of change in tidal amplitude is significant because in some estuaries that have been modified the tidal range change has been large. The tidal range in Wilmington has increased about 0.57 m since 1887 due to dredging (Famikhalili and Talke, 2016; Talke and Jay, 2020). The stationarity of the tidal amplitude over time is helpful information when considering what factors are influencing flooding in Georgetown today compared to the past. The stationarity of tidal amplitudes in Winyah Bay demonstrates that any increase in flooding between the historic and modern records is most likely due to an elevated RSL.

Seasonally, changes in tides are important drivers of RSL both at the mouth of Winyah Bay as well as in the harbor. Sweet et al. (2018) characterized seasonal trends in higher tides throughout the southeast Atlantic Coast as periods when seasonal mean sea-level cycles are at their maximum (from September to November), and during the summer when tidal range increases around the summer solstice. These seasonal patterns are consistent with the ones identified in the T-TIDE predicted tides and measured water level for Winyah Bay and are helpful in considering periods of the year when increased nuisance flooding may occur (Section C, *Nuisance Flooding*).

Annually, changes in precipitation and discharge are correlated with changes in RSL in Winyah Bay as well as other regional coastal gauges near rivers such as Wilmington and Charleston. Meade and Emery (1971) examined the relationship between river discharge and coastal RSL and determined that river discharge may explain 20-31% of RSL variations annually. Piecuch et al. (2018) sought to confirm the results of the 1971 study and explain the physical dynamics of the relationship. These authors took a regional approach and found for each region (northeast, mid-Atlantic, southeast) the correlations were significant. Although the South Atlantic Bight had the weakest correlation coefficient of 0.24, the relationship was still statistically significant. They proposed that the relationship is driven by river plume volume. Seasonally, an increase in precipitation in the Pee Dee watershed from March to October coincided with higher water levels in Winyah Bay, even when excluding tides, which may also be elevated during that time period. This relationship is significant because higher seasonal levels in river discharge forcing higher base water-levels in Winyah Bay can cause minor to major flood events due to a combination of discharge, wind and tides (Section D, *Minor and Major Flooding Events*).

The rivers connect the ocean to the rest of Georgetown County. Results in this study showed a significant modern increase in water level at most of the gauges in the Waccamaw River at a rate of 3-7 mm/year. This finding could be evidence for either RSL rise also happening further upstream or an increase in discharge due to climatic reasons. There is not a significant long-term trend in water level at the Longs gauge, which also shows little to no influence from tides. The increasing water-level trends seen at the stations lower on the Waccamaw can most likely be explained by RSL rise. The increase of 3-7 mm/year in water level in the rivers is consistent with the 4.6 mm/year RSL rise rate calculated from the tide-gauge records in Winyah Bay. Rising water levels within the lower river reaches could contribute to increasing flooding in the low-lying communities on the floodplain of the Waccamaw River outside of the City of Georgetown.

Considering the relationship between tidal range and discharge as well as how it changes spatially over the length of the bay is important in understanding which of these factors is most important in controlling flooding in the City of Georgetown. Despite the difference in magnitude of tidal range between the NERR station and USGS Georgetown station, the relative change in tidal range compared to high discharge events appears to be similar. During some high discharge events there is a decrease in tidal range, although, this relationship does not seem to always hold true, and thus, there is a lack of linear relationship between these two variables (Fig. 28). During the storm event in September of 2019 (Hurricane Dorian) a decrease in tidal range occurred at both the NERR station as well at the Pee Dee station in Georgetown however the NERR station first showed an increase in tidal range before the high discharge event occurred (Fig 27). The increase in tidal range at the NERR station before the event could be due to the wind-blown storm surge causing higher and then lower water levels as the storm moved over Winyah Bay. The event-scale relationship between discharge and tidal range during Hurricane Dorian demonstrates that the storm surge was not superimposing on top of the tidal signal (i.e. decreasing the tidal range) but rather amplified the range between the high tide and low tide. Then, as the new pulse in river discharge reached the bay the tidal range decreased. In summary, the relationship between these two mechanisms is complicated and different types of events (discharge, precipitation and wind) appear to cause different responses in tidal range (Fig. 27, 28). Due to the complicated relationship between these two variables during storm surge, they must both be considered individually when describing their effects on flooding in the City of Georgetown.

Coastal RSL appears to have a linear relationship with RSL at the mouth of the bay as well as the back of the bay near the harbor. Some data points exhibit variance from the linear relationship and fall above the ideal relationship line which may be related to high-discharge events or local wind increasing water level. The relationship between coastal RSL and RSL inside Winyah Bay is significant because coastal RSL can vary seasonally and annually related to mechanisms such as Gulf Stream dynamics, NAO index and AMOC (Ezer et al., 2013; Goddard et al., 2015). Seasonal trends in coastal water level can increase the base water-level for flooding in Georgetown.

C. Nuisance Flooding in Georgetown– Results

Analysis of the historic nuisance flood water level modeling showed that predicted tides plus the yearly mean sea level for 1899 and 1900 produced no water levels over the elevation thresholds for 901 Front Street or the corner of Front Street and Greenwich Drive (Fig. 32).

The analysis of the nuisance flood water level modeling for 2017-2019 showed that nuisance flooding occurred at the three measured elevation levels (Fig. 33). A projected difference of a remarkable 1,007 additional hours of nuisance flooding occurred between 2019 and 2017 at the corner of Front Street and Greenwich Drive and 71 hours at 901 Front Street. A projected additional 1,046 hours of nuisance flooding occurred at the MHHW level in 2019 compared to 2017. Front Street and Greenwich Drive flooded on 332 days in 2017, 347 days in 2018 and 263 days in 2019 due to tides and RSL. Projected nuisance flooding occurred 1 day at 901 Front Street in 2017, 4 days in 2018 and 42 days in 2019 (Tab. 10). Nuisance flooding occurred more often from December to March in the modern record.

RSL and tides in Georgetown in the year 2039 were modeled and used to predict nuisance flooding in 20 years. The prediction showed that nuisance flooding will probably increase by about 867 hours per year at the corner of Front Street and Greenwich Drive and by approximately 304 hours per year at 901 Front Street when comparing the 2019 analysis to the 2039 prediction (Fig. 34). Based on this modeling, nuisance flooding will occur 365 days a year at the corner of Front Street and Greenwich Drive and 363 days a year to the level of MHHW. Flooding at 901 Front Street will occur 160 days/year based on tides and RSL alone. This forecast indicates that nuisance flooding will occur on 118 additional days at 901 Front Street in 2039 compared to 2019 (Fig. 35). Predicted nuisance flooding will continue to occur mainly from December until March and also become more prominent during higher tides from May to October (Fig. 34).

Nuisance Flooding in Georgetown – Discussion

The comparison of past and present nuisance flooding conditions shows that under rising RSL, flooding has increased in low-lying areas. These flooding events, although they could last as short as an hour, occurred more frequently during the short period between 2017 and 2019 due to a slight increase in RSL, possibly also controlled by cyclically elevated water level due to oceanic currents and an increase in precipitation (Section A, *Relative Sea Le*vel and Section B, *Hydrography of Winyah Bay*). This variability shows interannual drivers of RSL and their implications for flooding must be considered in addition to a global sea level rise and regional land lowering mechanisms. Discharge and precipitation vary from 'wetter' to 'drier' periods based on climatic cycles (Bales and Pope 2001; NOAA NCEI, 2020). The precipitation cycles vary approximately every 20 years and can deviate from the long-term average ± 13 cm (5 in) (NOAA NCEI, 2020). Precipitation has been increasing since 2011 and is likely in a 'wetter' phase where precipitation and discharge will be relatively high for the next decade based on the recent trends in annual precipitation in SC and climatic cycles such as NAO. Considering this cyclicity, precipitation and discharge may contribute to higher RSLs from 2011-2031 and then could enter a drier phase from 2031-2051 when these mechanisms are not contributing as heavily to local RSL.

The South Carolina Department of Health and Environmental Control (DHEC) monitors King Tide predictions and occurrences for coastal communities throughout the state (DHEC, 2020). In 2017 they predicted 26 king tides and observed 128. For 2018, they predicted 41 and observed 108 and for 2019 they predicted 37 and observed 178. The relationship between their predictions (based on NOAA tide predictions) and observations is most likely affected by the increase in MSL over the three years observed in this study. Their predictions and observations match the results presented in this study in terms of an increase in tidal flooding from 2017-2019. The results are however difficult to compare because they lack a local elevation reference in the Georgetown/Winyah Bay region. Ray and Foster (2016) studied nuisance flooding due to astronomical tides and noted that some clusters of years were more prone to tidal flooding than others due to the 4.4-year modulation of tides related to the lunar perigee precession. This tidal cycle will lead to some years that experience less flooding due to exclusively tides but then the tidally influenced flooding will return and become more noticeable (Haigh et al., 2011; Talke et al. 2018).

Springmaid Pier is the closest location to Winyah Bay where nuisance flooding has been modeled, and be used for comparison to the results presented here. Sweet et al. (2014) analyzed NOAA tide gauges along the East Coast and found that nuisance flooding events are increasing and the rate of increase is accelerating at many gauges. For the Springmaid Pier site they showed that nuisance flooding occurs most frequently from October-January and in June and July. This seasonal pattern is consistent with the seasonal trends seen in the results here. Dahl et al. (2017) analyzed tidal flooding at tide gauges along the East Coast using the NOAA online Inundation Analysis tool and projected RSL rise. They found a statistically significant increase in flooding will occur at 38 of the 52 sites from 2017 to 2030, and that the yearly number of high tide flooding events will triple by 2030 at some of those gauges. For Springmaid Pier they projected an increase from 3 flooding events/year to 13 events/year by 2030 and 57 events/year by 2045.

The prediction of future nuisance flooding in Georgetown shows that the area near the intersection of Greenwich Drive and Front Street will flood due to tides alone nearly every day of the year over the next two decades. This flooding will last for several hours a day making homes and other infrastructure inaccessible. Flooding will occur almost half of the days of the year at 901 Front Street which is located in the center of the historic waterfront area. Nuisance flooding, even if for a few hours each day, will be a significant challenge for businesses and restaurants in the area who rely on foot and vehicle traffic as well as access to their storefronts on Front Street.

D. Minor and Major Flooding in Georgetown – Results

Examination of the historic water-level data for Georgetown showed that unlike the results for nuisance flooding (based on RSL and tides only), flooding would have occasionally occurred during 1899 and 1900 at Front Street and Greenwich Drive from the combination of tides, discharge and atmospheric drivers (Fig. 36). This flooding was most concentrated during the winter months of both 1899 and 1900. Flooding occurred 168 hours more at the modern Front Street and Greenwich Drive level in 1899 than in 1900. There were instances of a few hours of flooding at the modern 901 Front Street in 1899 but none in the 1900 modeling.

Analysis for the 2017-2019 water-level data showed that flooding at Front Street and Greenwich Drive occurred almost every day except for when water levels are very low (Fig. 37). Flooding occurred at 901 Front Street during the winter months and during events in June to October. There were 1,375 additional hours of flooding at Front Street and Greenwich Drive in 2017 than in 1899. In the modern record, there were 863 additional hours of flooding in 2019 compared to 2017 at Front Street and Greenwich Drive. There were 148 additional hours of flooding at 901 Front Street in 2019 than in 2017.

Modeling for future water levels using predicted tides for the private dock, a projected RSL using the land lowering rate calculated for Winyah Bay and an annual global sea-level rise rate of 3.3 mm/year showed that flooding occurred for a majority of the year for at least few hours a day at all three elevation levels (Fig. 38). Flooding occurred for 1,662 more hours in 2039 at Front Street and Greenwich Drive than in 2019. Flooding occurred 1,719 more hours above MHHW in 2039 compared to 2019. 901 Front Street flooded for 1,049 more hours in 2039 than in 2019. Overall, there were 6 times the number of hours of flooding in 2017 compared to 1899 and 16 times the number of hours of flooding in 2039 compared to 1899 at Front Street and Greenwich Drive (Fig. 39).

Storm events were compared from the historic and modern record by removing tides and mean sea level from the records and examining events greater than two standard deviations of the mean. There were approximately 24 storm events in 1899 and 13 events in 1900 (Fig. 40). In the modern record, there were 12 storm events in 2017, 14 storm events in 2018 and 23 storm events in 2019 (Fig. 41). The size of the storm events in the historic and modern records were approximately the same change in water level, with the largest storms of each record elevating water levels about 1 m.

Minor and Major Flooding in Georgetown – Discussion

Minor flooding may have historically occurred at Greenwich Drive and Front Street due to a combination of tides and higher water levels from discharge and wind when comparing the 1899-1900 and 2017-2019 tide-gauge records. The flooding was more concentrated during November to January which is a period when tides are elevated in Winyah Bay. During events in May to September flooding may have occurred for an hour or two from a combination of extreme freshwater discharge, local wind and high tides. This pattern is consistent with times when precipitation in the Pee Dee Watershed is elevated and when seasonally higher tides can also occur.

In the 2017-2019 record, flooding increased each year due to an elevated RSL. The increase in RSL may be related to an increase in precipitation, discharge and ocean currents over the same period. This relationship demonstrates the importance of climatic cycles when considering flooding over multiple years. Seasonally, flooding occurred during times of the year when tides were generally higher as well as when precipitation was higher

(Section A, *Relative Sea Le*vel and Section B, *Hydrography of Winyah Bay*). Burgos et al. (2018) showed that flooding from RSL rise, tides and climate variability controlling the Gulf Stream significantly shifts the timeframe of flooding in Norfolk, VA after 2030 when considering tides alone to before 2030 when considering the climatic variability. This study acknowledged that flooding already occurs due to these factors with a high wind event or storm event contribution. This shows that when considering flooding in the future, it is important to understand the cyclic contributions (such as climate and tidal nodes) as well as event scale contributions to water level. During 2017-2019, flooding occurred more frequently at 901 Front Street during November to January, a time period when tides are generally higher in Winyah Bay and when flooding occurred in the historic record. Flooding also occurred at this location in September and October, this flooding is most likely due to elevated discharges and wind from the major hurricanes that cause an increase in precipitation in the watershed. The 2039 prediction using the non-tidal residuals from 2019 with the predicted tides and an estimated RSL shows that flooding may occur almost every day due to a combination of an elevated RSL, tides and discharge or wind. This is an important message to deliver to the businesses and homeowners in the City of Georgetown, many of whom may still own the property which they own now in 20 years. This prediction indicates that planning for RSL rise and consequently flooding all over the city needs to be done soon in order to secure the city for the near future.

Storm events greater than two standard deviations of the mean of the storm residuals occurred more often in the winter when water levels were already elevated and storm events more easily reached that threshold. This pattern occurred both in the historic and modern records. Hurricanes or tropical storms that occurred in the data each had different effects and patterns in terms of water-level response. This demonstrates that wind direction and atmospheric pressure can either cause a lower water level first then a peak or a peak first then a decline in water level. Some storms had just a storm surge response and others had an elevated water level for a longer period of time due to precipitation and discharge from the rivers. Kemp and Horton (2013) showed that timing of the tide and RSL play a large role in how flooding occurs during hurricanes in New York City. The role of tides and RSL could explain the differences between storm height during the hurricane in 2018 and 2019 in the modern record. Talke et al. (2018) showed that RSL rise is the most important factor for increasing flooding risk in Boston. The historic storm events which they analyzed had higher water levels than the modern mean high-water datum. In Georgetown, a similar phenomenon can be observed when RSL and tides are removed from both the historic and modern data so there is not a large difference in storm height.

There was not a large increase in the number of storm events between the historic and modern records. Zhang et al. (2000) analyzed storm events at tide gauges all along the East Coast and found that based on linear regression results there were no significant long-term trends in the amount or duration in storm events annually.

CONCLUSIONS AND OUTLOOK

From short period historic and modern water level data RSL rose 0.55 m between 1899 and 2019 at the Georgetown Lighthouse in Winyah Bay. The calculated long-term linear rate of *RSL rise was 4.6 ± 0.6 mm/year* and the long-term linear rate of *subsidence was 2.9 mm/year*. The rate in RSL rise in Winyah Bay was shown to be higher than the rates in Wilmington, NC and Charleston, SC (Tab. 2). Regional differences in the historic rate of RSL rise are most likely related to differences in subsidence which was previously calculated to range from -0.43 mm/year in Wilmington, NC to -2.34 mm/year in Myrtle Beach (Tab. 2; Zervas et al., 2013). Differences in subsidence between Wilmington, NC and central and southern South Carolina has been attributed to the uplift of the Cape Fear Arch which occurs at a rate of approximately 0.24 ± 0.15 mm/year (Van De Plassche et al., 2014). The extent to which the uplift of this feature contributes to RSL variations in Winyah Bay on a historic time scale has not been quantified and is difficult to estimate. The regional differences in subsidence between Winyah Bay and Charleston may be caused by differences in sediment compaction. Groundwater extraction could be one mechanism that contributes to this regional variability, as subsurface water-level declines in Horry and Georgetown Counties (0.73 m/year) are almost twice as large as those in Charleston County (0.425 m/year) (Berezowska and Monroe, 2017). The relationship between subsurface water-level decline and subsidence is difficult to quantify, however, because it depends on several factors including the depth of the aquifer and the underlying lithology.

Decadal rates of RSL rise were analyzed regionally and broken into mechanisms (i.e. global sea level rise, subsidence rates, oceanic variation trends) in order to examine the extent to which individual mechanisms can change the rate of RSL rise. Oceanic variations (such as coastal ocean currents, water temperature, salinity and density) contributed both positively and negatively in the coupling of components contributing to the rate of RSL rise on a scale of -3 to 10 mm/year (Tab. 3; Fig. 21). Eustatic sea level rise has increased from 1.7 mm/year during the 20th and early 21st century to 3.3 mm/year and is projected to continue to increase (Church and White, 2011; Horton et al. 2020). Currently, with the ‘positive’ coupling of several mechanisms that may lead to a RSL rise of more than 15 mm/year, marshes and wetlands around Winyah Bay may become more vulnerable to substrate erosion and drowning; vulnerability to flooding has already increased in the City of Georgetown, as this study shows, and all along the coast.

Further research needs to be completed to fill in the time gap in data from 1904-2017 to analyze how the rate has changed over the past decades. Winyah Bay, surrounded by marshes and adjacent to the marshes of North Inlet, the Santee River system and Cape Romain, is an appropriate location for a geologic, RSL reconstruction. In the future, the work begun during this project with sediment cores SJM_02, SJM_03 and EMB_01 can be used to address this data gap. Core EMB_01 is particularly suited for this reconstruction because the ^{210}Pb excess model showed that the nearly 1-m long core spans the same time frame as the time period analyzed here, i.e. from the late 20th century to 2019. Foraminifera extracted from the sediment cores could be used to establish past sea-level elevation by linking the species in the cores to the modern distribution of foraminiferal species. A transect of modern surface sediment samples in Mud Bay has been completed and could be used as a modern analog for the zonation of foraminiferal species in the marsh today.

The rate of local subsidence could also be addressed by using methods separate from the tide gauge record to validate and further explore temporal RSL rate calculated in this project. Georgetown is a historic city and has benchmarks all over the area with some of them having been maintained since the early 20th century. Analyses of these benchmarks using the datasheets from the National Geodetic Survey (NGS) and measurements taken using the RTK-GPS technology could be used to calculate the rate in local subsidence for the City of Georgetown.

Due to the complex hydrography of Winyah Bay, characterizing the water-surface gradient as well as seasonal cycles of tides, discharge, precipitation and coastal water levels is useful for understanding the vulnerability of the community to flooding. The surface gradient of water level increases from the mouth of the bay at Georgetown Lighthouse to the back of the bay (Tab. 5). There is also a decrease in tidal range from Georgetown Lighthouse to the City of Georgetown (Tab. 5). The implications of this finding are a lower threshold for flooding in the City of Georgetown due to an elevated base RSL on the one hand, but high tides will have weaker influence compared to what areas around the mouth of the bay experience.

The seasonal cycle in the monthly averaged tides changes water levels on the scale of 0.1 to 1 cm with tides generally higher from March to May and September to November (Fig. 23). Analysis of historic and modern tidal constituent amplitudes showed that the tidal range has been stationary over time, implying that any increase in flooding in the City of

Georgetown from 1899-2019 is due to a rising RSL as opposed to a change in tidal amplitudes (Tab. 1, Appendix).

Precipitation and resulting fluvial discharge also are important factors when considering inter-annual and seasonal changes in water levels in Georgetown because of the 5 rivers that discharge into the estuary. Inter-annual variations in precipitation were shown to correlate positively with inter-annual variations in water level at the tide gauges in Wilmington and Charleston, and it is assumedly the same relationship in Winyah Bay (Fig. 25). On a seasonal scale, precipitation in the Pee Dee River watershed was highest from January to March, June to July and August to September (Fig. 26). Seasonal cycles in precipitation contribute seasonally to RLS rise in Winyah Bay

Water level has increased over the past 10 years at several USGS stations along the Waccamaw River which could be attributed to either an increase in fluvial discharge or the RSL rise having an influence over a certain distance upstream (Fig 24). RSL rise in the lower-course of the Waccamaw is an important planning consideration for the communities of Georgetown County located along the river.

Coastal RSL was shown to follow the same seasonal trends as water level both at the mouth and in the back of Winyah Bay (Fig 30, Fig. 31). Coastal RSL at Springmaid Pier experienced higher seasonal levels from February to April and August to October which is similar to the seasonal cycle noted in precipitation (Fig. 29). Differences occurring between Winyah Bay water level and coastal RSL on short time scales (over days or weeks) are most likely caused by high discharge events or high local wind events.

External forcing mechanisms such as wind speed, wind direction, river discharge and atmospheric pressure play a role in changing water levels on an event scale. Depending on the magnitude and direction of each of these processes, a ‘positive’ correlation of several of these atmospheric variables can amplify flooding in Georgetown. Particularly discharge should be investigated at weekly to daily time scales in order to understand the role it plays in changing RSL on a short-term basis, such as during storm surge. Other drivers of RSL not examined here, such as atmospheric pressure, wind speed and wind direction can cause high water levels on a scale of days to weeks and thus are also critical in order to characterize what combined dynamics determine the flood inundation hazard in the City of Georgetown. The tide gauge data from the NERR station as well as Private Dock could be used in conjunction with the USGS discharge data and NERR meteorological station wind and atmospheric pressure data to analyze the relationship between these variables and flooding in a series of small-scale case studies. These case studies would further the understanding of those mechanisms most important in causing flooding for the City of Georgetown.

The seasonal cycle of tides and as well as inter-annual variations in RSL promote nuisance flooding in the City of Georgetown. Nuisance flooding has become a problem in several cities along the East Coast due to rising RSL and has been increasing in both frequency and duration in recent years (Sweet et al., 2014; 2018). Based on modeling of tides for the historic tide-gauge record of 1899-1900 results show that nuisance flooding (due to tides and MSL) would not have occurred in the City of Georgetown at that time (Fig. 32). Nuisance Flooding, however, occurred downtown at 901 Front Street as well as in the community near East Bay Park at the corner of Front Street and Greenwich Drive in 2017-

2019, and it significantly increased at these locations over the three-year record due to inter-annual variations in coastal and fluvial water level (Fig 33). Nuisance flooding is concentrated from December to March and during Spring Tides from May to October. Modeling of flooding in Georgetown due to variations in water level associated with atmospheric pressure, wind and discharge showed that flooding only occasionally occurred in 1899-1900 at 901 Front Street and the corner of Front Street and Greenwich Drive (Fig. 36). Using the 2017-2019 record the approach showed that, in addition to the above-mentioned seasonal cycle of nuisance flooding, flooding occurred during September to October due to increased precipitation and discharge related to Hurricane Dorian (Fig. 37). A projection for the year 2039 showed that flooding will occur for a majority of the year at both 901 Front Street and the corner of Front Street and Greenwich Drive from a combination of RSL rise, tides, atmospheric pressure variations, local wind forcing, and river discharge (Fig. 38). This modeling displays the importance of urban and infrastructure planning, which should occur in the next 25 years (based on RSL rise as well as climatic cycles that control precipitation and discharge) to protect local homes and businesses in the City of Georgetown.

Future research needs to be conducted to verify these model results and to ground-truth the accuracy of the projection of timing and duration of nuisance flooding in Georgetown. A request flyer was disseminated to residents of the City of Georgetown in March 2020 inquiring about when and to what extent flooding has occurred on their property. As similar activity is under preparation with SC DHEC to gather this kind of information though a webpage. Communication with these residents should continue and the information should be collected and used to validate and calibrate the nuisance flooding model presented here. A water-level logger or camera could also be installed at 901 Front Street and the corner of Front Street and Greenwich to collect data to calibrate the projections of flooding throughout the city.

TABLES

Table 1: Historic and modern tidal statistics at the Georgetown Lighthouse site. Water level is given in meters and related to the NAVD88.

Tidal Statistics (m)	1899	1900	1901	1902	1903	1904	Historic Range	NERR 2017	NERR 2018	NERR 2019	Modern Range (NERR)	2019 Lighthouse
MTL	-0.48	--	-0.51	-0.49	-0.45	-0.49	0.06	---	--	--	--	--
MSL	-0.53	-0.55	-0.56*	-0.54*	-0.50*	-0.54*	0.02	-0.02	0.02	0.10	0.12	0.03
MHW	-0.03	-0.07	0.03	0.02	0.08	0.03	0.15	0.48	0.51	0.60	0.12	0.60
MLW	-1.00	-1.00	-1.05	-1.02	-0.99	-1.02	0.07	-0.58	-0.50	-0.41	0.17	-0.54

*MSL was estimated using the difference between 1899 MTL and MSL

Table 2: Comparison of regional tide gauge records (Data from NOAA Tides & Currents, 2020).

Station Comparison	Georgetown Lighthouse	Springmaid Pier	Charleston, SC	Wilmington, SC
Record length	1899-1904, 2017-2019	1954-2019	1899-2019	1908-2019
RSL rise rate (mm/yr)	4.6	3.96	3.32	2.47
Subsidence rate (mm/yr)	-2.9	-2.34	-1.24	-0.43
Distance from Georgetown Lighthouse (km)	-	89	135	258

Table 3: Comparison of relative SLR measured at NOAA tide gauges at Charleston, Myrtle Beach (Springmaid Pier) and Wilmington during the periods 1993-2013 and 2009-2019. Calculated RSL rise is the sum of the rates of oceanic inter-annual variability, global sea level rise and subsidence rates. Linear regression of annual RSLR and inter-annual variations used to calculate rates at each tide gauge to compare to measured RSLR.

NOAA Tide Gauge	Measured RSLR (mm/year)	Oceanic Variations (mm/year)	GSLR (mm/year)	Subsidence rate (mm/year)	Calculated RSLR (mm/year)	Difference in measured and calculated RSLR (mm/year)
Charleston 1993-2013	3.01	-1.3	2.8	1.4	2.9	-0.11
Charleston 2009-2019	14	9.8	3.3	1.4	14.5	0.5
Springmaid 1993-2013	1.7	-2.3	2.8	2.9	3.4	1.7
Springmaid 2009-2019	9.2	5.2	3.3	2.9	11.4	2.2
Wilmington 1993-2013	0.4	-2.2	2.8	1.5	2.1	1.7
Wilmington 2009-2019	15.6	9.3	3.3	1.5	14.1	-1.5

Table 4: Trends in relative sea level rise and oceanic variability quantified using linear regression and a linear average calculation for the periods 1993-2013 and 2009-2019 at Springmaid Pier in Myrtle Beach and Wilmington NC in order to show statistical uncertainty in the calculation of trends over short time periods.

Trend, Location and Period	Linear Regression rate (mm/year)	Linear Average Rate (mm/year)
RSLR Springmaid 1993-2013	1.7	1.9
RSLR Springmaid 2009-2019	9.2	9.9
RSLR Wilmington 1993-2013	0.4	1.7
RSLR Wilmington 2009-2019	15.6	15.9
Oceanic Variability Springmaid 1993-2013	-2.3	-1.9
Oceanic Variability Springmaid 2009-2019	5.2	5.9
Oceanic Variability Wilmington 1993-2013	-2.2	5.5
Oceanic Variability Wilmington 2009-2019	9.9	-10.3

Table 5: Comparison of RSL referenced to NAVD88 showing the gradient of water surface level from the Waccamaw River and along Winyah Bay in 2019.

Station	MSL (m)	MHW (m)	MLW (m)	TR (m)
Waccamaw @ Socastee*	0.45	0.63	0.17	0.32
Waccamaw @ Pawleys Island	0.35	0.70	-0.10	0.79
Private Dock**	0.28	0.77	-0.24	1.00
NERR	0.10	0.60	-0.41	1.01
Georgetown Lighthouse	0.03	0.60	-0.54	1.14

*A large storm event was removed. **Not a complete year of record.

Table 6: Calculation of water surface gradient in Waccamaw River and Winyah Bay.

Station	Distance (km)	MSL(m)	Gradient between stations (mm/km)
Georgetown Lighthouse	--	0.03	--
Private Dock**	17.39	0.28	14
Waccamaw near Pawleys Island	21.42	0.35	3
Waccamaw near Socastee*	23.2	0.45	4
Buck Creek near Longs*	39.48	3.35	73

* large storm events were removed. **Not a complete year of record.

Table 7: Regression results for water level in the Waccamaw River for two periods and their associated p-values (locations shown on Fig. 13).

Station	Rate 2001-2019 (mm/yr)	t-statistic	p-value	Rate 2005-2019 (mm/yr)	t-statistic	p-value
Longs	10.24	1.7094	0.10	13.86	1.7981	0.095
Conway	5.52	3.5757	0.002	6.89	3.7651	0.002
Socastee	2.47	6.0554	0.000	2.47	3.8974	0.002
Bucksport	--	--	--	3.38	4.8712	0.001
Pawleys Island	3.20	6.1574	0.000	3.29	4.5212	0.001
Pee Dee Bucksport	0.004	0.1964	0.848	0.002	0.086354	0.934

Table 8: Correlation coefficients and associated p-values for precipitation and yearly mean sea level.

Factors	R value	P value
SE Precipitation and Charleston yearly mean sea level (1935-2019)	0.3948	0.0002
SE Precipitation and Willington yearly mean sea level (1935-2019)	0.5444	0.0000

Table 9: Correlation coefficients and associated p-values for coastal water levels (Springmaid Pier) and proximal and distal Winyah Bay water levels.

Locations	R	P-value
Springmaid Pier, Private Dock	0.5166	0.00
Springmaid Pier, NERR	0.6419	0.00

Table 10: Number of days of nuisance flooding occurred over the period of 2017-2019 for the three elevation levels.

Flooding Level	2017 days flooded	2018 days flooded	2019 days flooded
Greenwich Drive, Front Street	332	347	363
MHHW	219	292	338
901 Front Street	1	4	42

FIGURES

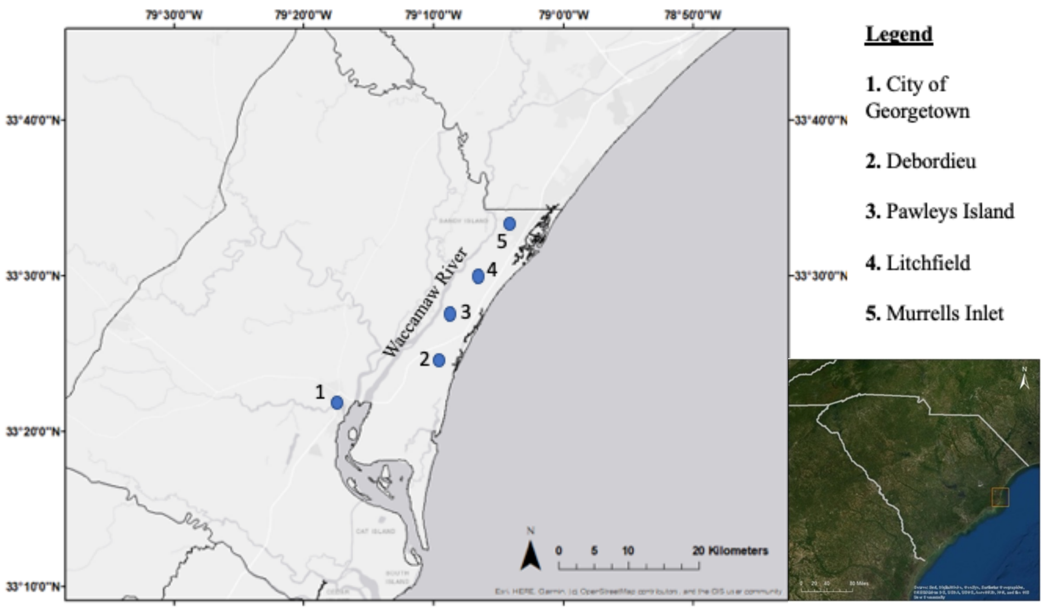


Figure 1: Map of Georgetown County with communities of Debordieu, Pawleys Island, Litchfield, Murrells Inlet and the City of Georgetown identified with blue circles. Map of South Carolina with Georgetown County highlighted with a yellow box for reference.

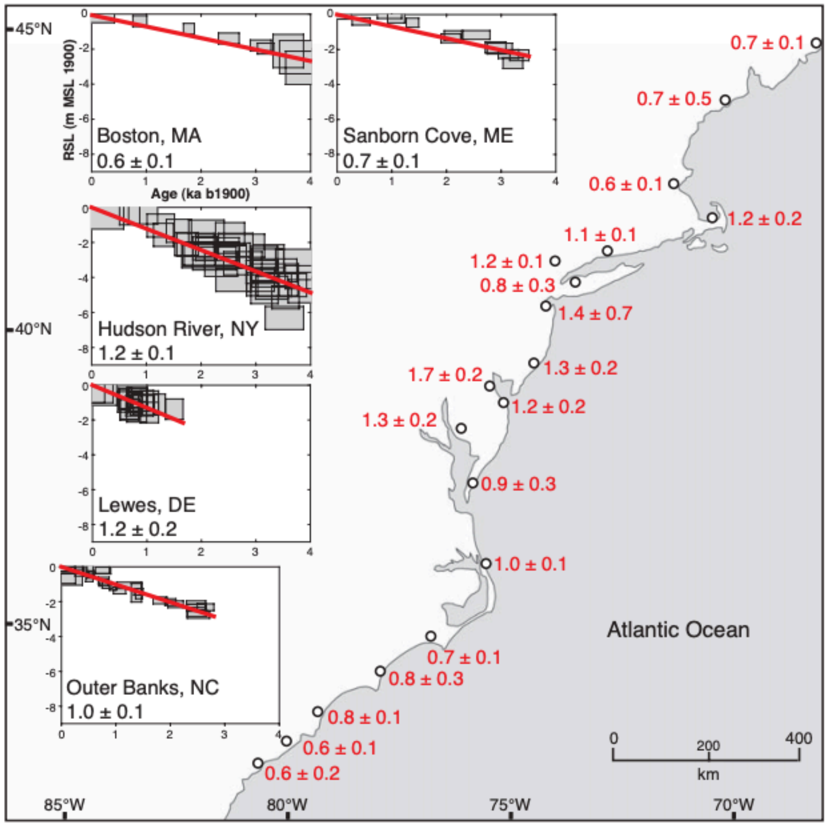


Figure 2: Spatial variability of late Holocene relative sea-level rise rates and 2 standard deviations (shown in red). Plots on the left side show individual sea-level reconstructions from sea-level index points (from Engelhart et al., 2009).

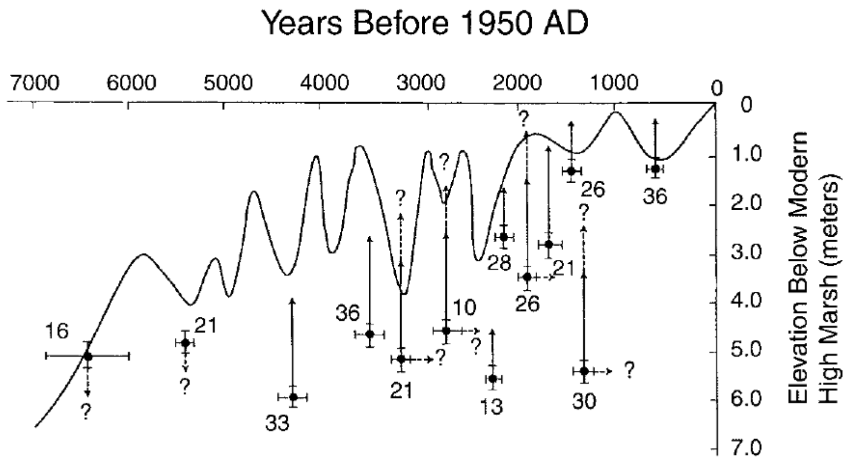


Figure 3: First and only sea-level curve for central South Carolina based on radiocarbon dating of oyster shells (solid line from Brooks et al. 1989) and data points with error bars indicating minimum elevation of high marsh (from Gardner and Porter, 2001). The solid line which denotes a fluctuating sea level does not comply with the approaches used for modern dating methods or SL reconstructions.

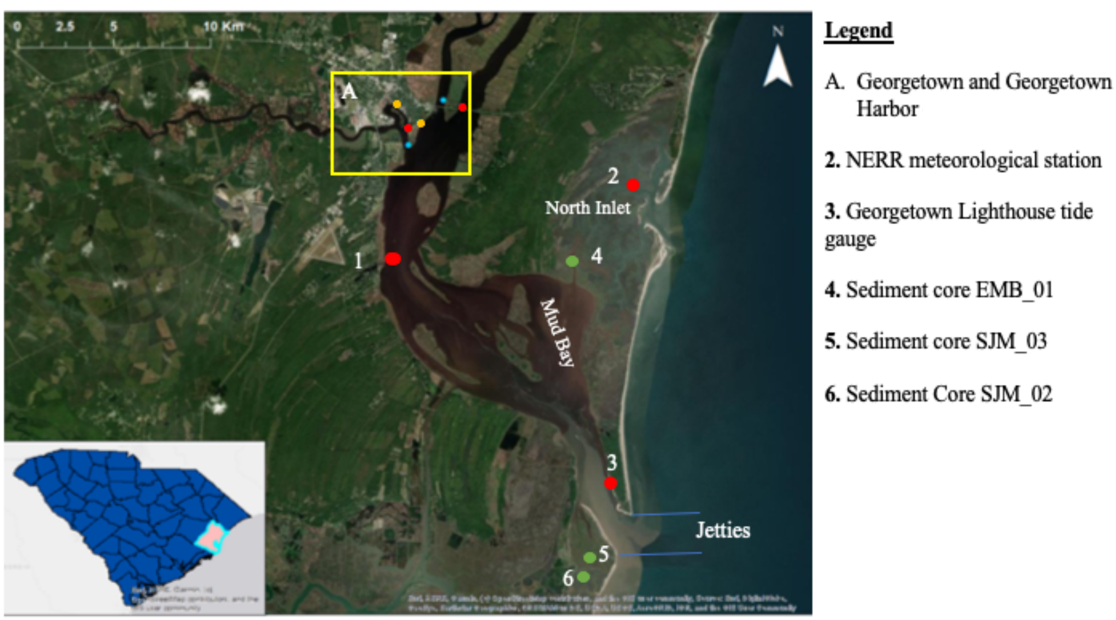
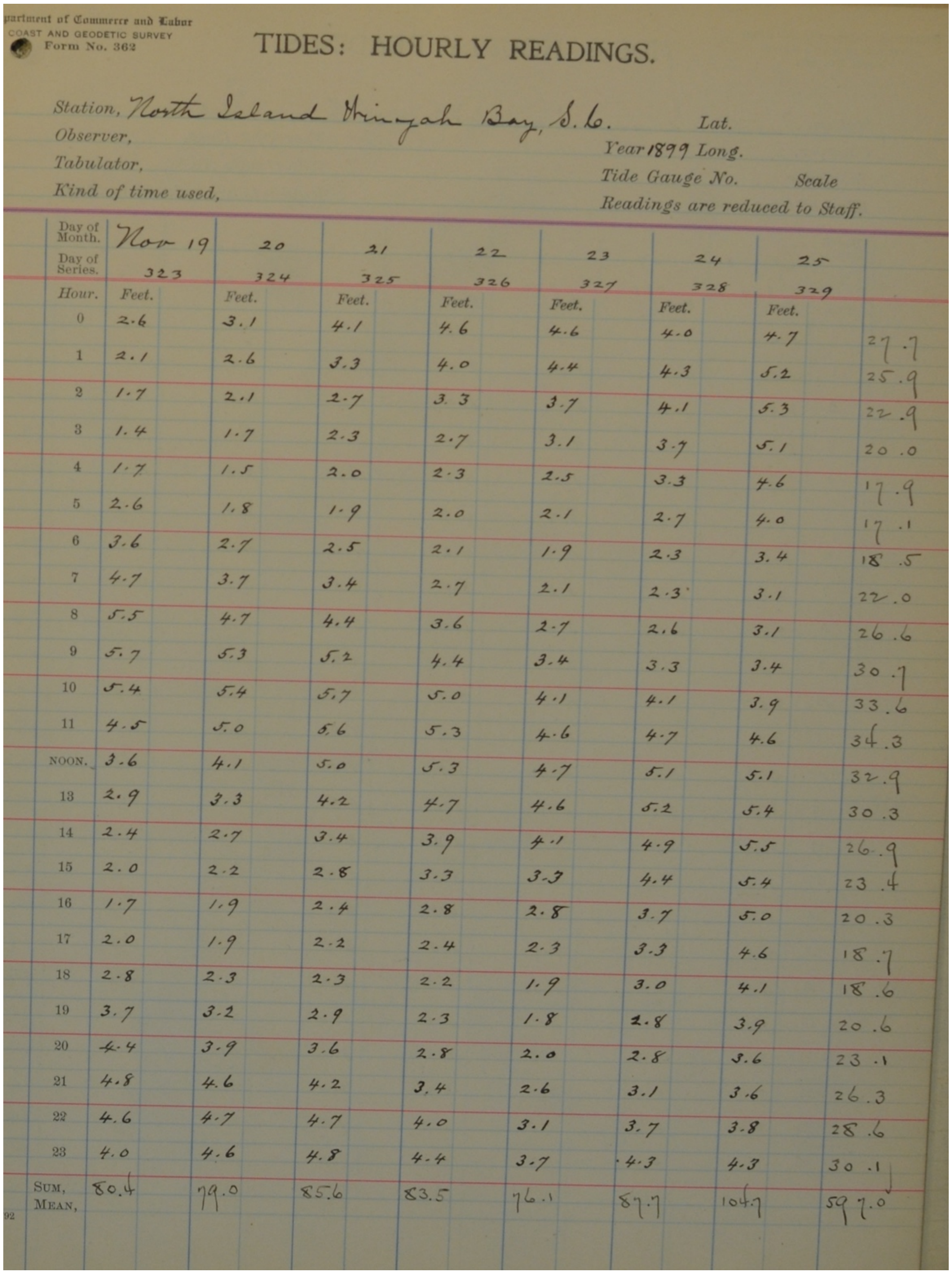


Figure 4: Satellite image of Winyah Bay with Georgetown Harbor highlighted with a yellow box. Tide gauges (red), NERR meteorological station (red) and location of sediment cores(green) denoted with circles. Base map with Georgetown County highlighted in pink is included for spatial context.



partment of Commerce and Labor
COAST AND GEODETIC SURVEY
Form No. 362

TIDES: HOURLY READINGS.

Station, North Island Winyah Bay, S.C. Lat.
Observer,
Year 1899 Long.
Tabulator,
Tide Gauge No. Scale
Kind of time used,
Readings are reduced to Staff.

Day of Month.	Nov 19	20	21	22	23	24	25	
Day of Series.	323	324	325	326	327	328	329	
Hour.	Feet.	Feet.	Feet.	Feet.	Feet.	Feet.	Feet.	
0	2.6	3.1	4.1	4.6	4.6	4.0	4.7	27.7
1	2.1	2.6	3.3	4.0	4.4	4.3	5.2	25.9
2	1.7	2.1	2.7	3.3	3.7	4.1	5.3	22.9
3	1.4	1.7	2.3	2.7	3.1	3.7	5.1	20.0
4	1.7	1.5	2.0	2.3	2.5	3.3	4.6	17.9
5	2.6	1.8	1.9	2.0	2.1	2.7	4.0	17.1
6	3.6	2.7	2.5	2.1	1.9	2.3	3.4	18.5
7	4.7	3.7	3.4	2.7	2.1	2.3	3.1	22.0
8	5.5	4.7	4.4	3.6	2.7	2.6	3.1	26.6
9	5.7	5.3	5.2	4.4	3.4	3.3	3.4	30.7
10	5.4	5.4	5.7	5.0	4.1	4.1	3.9	33.6
11	4.5	5.0	5.6	5.3	4.6	4.7	4.6	34.3
NOON.	3.6	4.1	5.0	5.3	4.7	5.1	5.1	32.9
13	2.9	3.3	4.2	4.7	4.6	5.2	5.4	30.3
14	2.4	2.7	3.4	3.9	4.1	4.9	5.5	26.9
15	2.0	2.2	2.8	3.3	3.7	4.4	5.4	23.4
16	1.7	1.9	2.4	2.8	2.8	3.7	5.0	20.3
17	2.0	1.9	2.2	2.4	2.3	3.3	4.6	18.7
18	2.8	2.3	2.3	2.2	1.9	3.0	4.1	18.6
19	3.7	3.2	2.9	2.3	1.8	2.8	3.9	20.6
20	4.4	3.9	3.6	2.8	2.0	2.8	3.6	23.1
21	4.8	4.6	4.2	3.4	2.6	3.1	3.6	26.3
22	4.6	4.7	4.7	4.0	3.1	3.7	3.8	28.6
23	4.0	4.6	4.8	4.4	3.7	4.3	4.3	30.1
SUM, MEAN,	80.4	79.0	85.6	83.5	76.1	87.7	104.7	597.0

Figure 5: Photograph of a page of the handwritten hourly tide gauge record from the Georgetown Lighthouse typical of the 1899 and 1900 records. Rows representing the hours the data were collected and the columns indicating the days the data were collected.

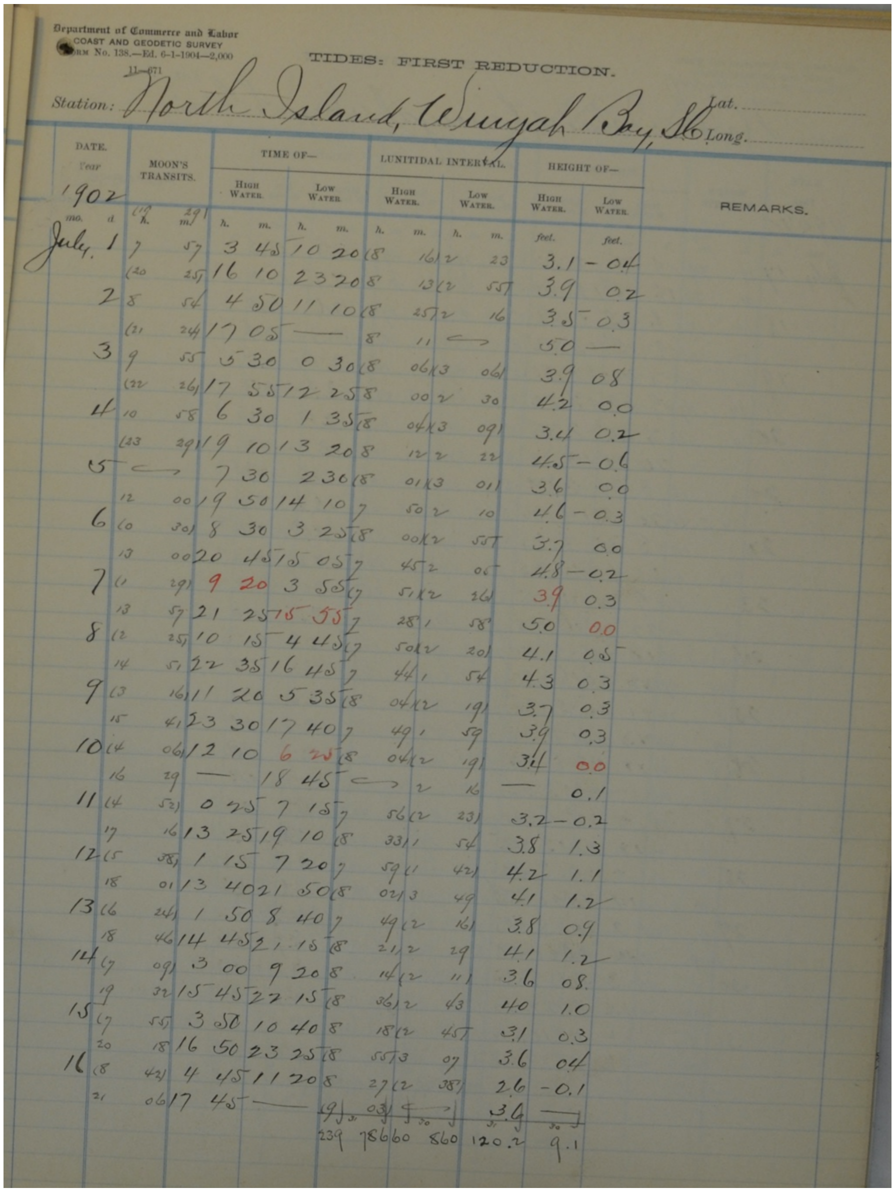
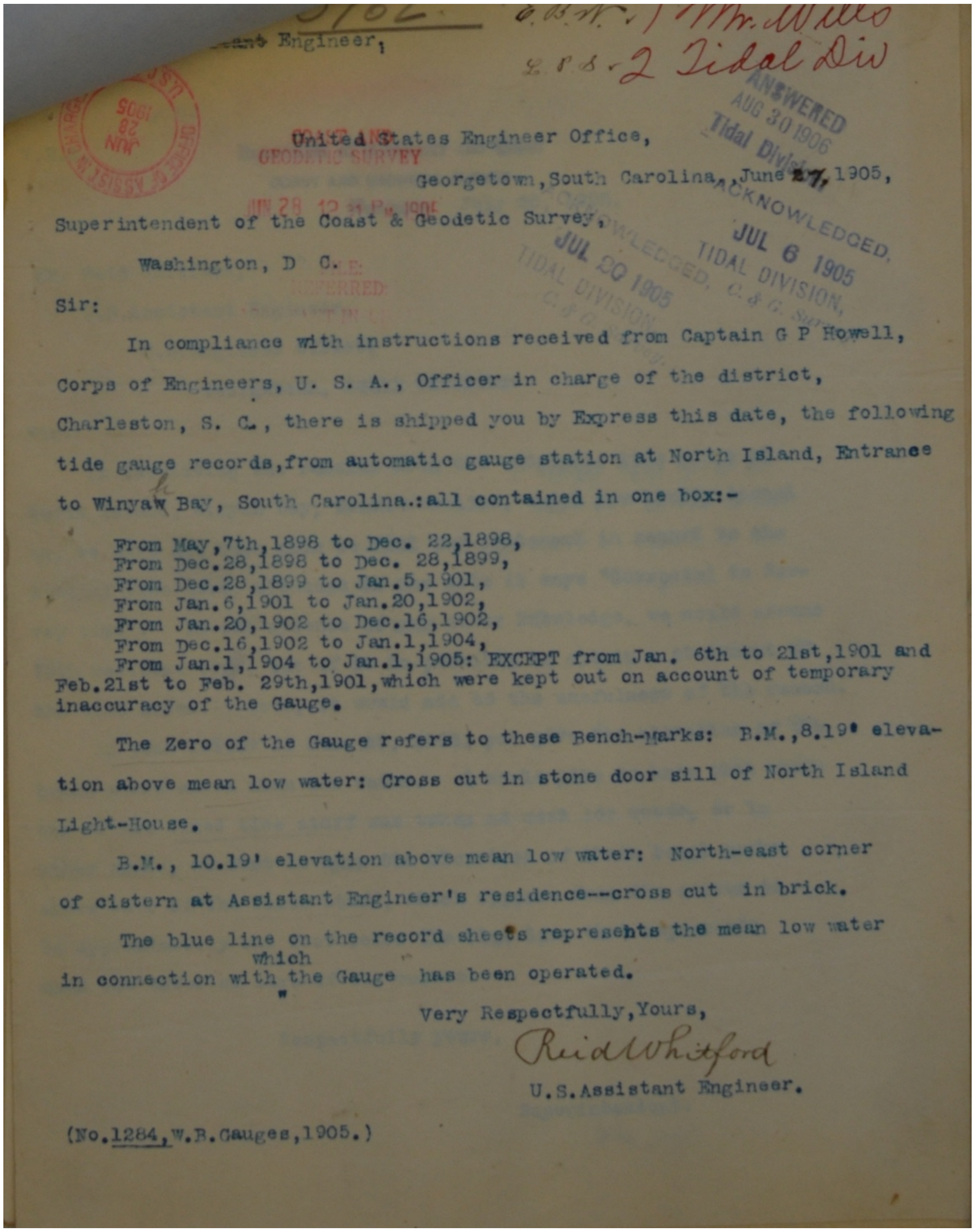


Figure 6: Photograph of a page of the twice daily high and low measurement tide gauge record from the Georgetown Lighthouse typical of the 1901-1904 records. Red ink indicates data that was missing or interpolated.

	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
1	1-Jan	2-Jan	3-Jan	4-Jan	5-Jan	6-Jan	7-Jan	8-Jan	9-Jan	10-Jan	11-Jan	12-Jan	13-Jan	14-Jan	15-Jan	16-Jan	17-Jan	18-Jan
2	NaN	NaN	2.0	2.6	3.4	4.0	3.9	3.7	NaN	2.6	1.2	0.9	0.4	1.2	1.2	1.6	2.2	3.2
3	NaN	NaN	1.5	2.1	2.6	3.7	4.1	4.1	NaN	3.5	2.1	1.5	0.6	1.0	0.9	1.2	1.7	2.7
4	NaN	NaN	1.0	1.5	2.0	2.8	3.7	4.2	NaN	4.4	3.1	2.3	1.5	1.2	0.6	0.9	**1.3**	2.2
5	NaN	NaN	0.6	1.0	1.4	2.2	2.9	3.6	NaN	4.7	3.9	3.2	2.4	1.9	0.7	0.8	1.0	1.9
6	NaN	NaN	0.3	0.6	1.0	1.6	2.2	2.7	NaN	4.6	4.3	4.0	3.4	2.9	1.5	1.2	1.0	1.7
7	NaN	NaN	0.5	**0.4**	0.6	1.1	1.7	NaN	NaN	4.1	4.3	4.4	4.0	3.9	2.5	2.2	1.6	2.0
8	NaN	NaN	1.4	0.7	0.5	0.7	1.3	NaN	NaN	3.2	4.0	4.2	4.4	4.4	3.4	3.1	2.7	2.9
9	NaN	NaN	2.6	1.9	0.8	0.6	1.0	NaN	NaN	2.6	3.1	3.5	4.4	4.8	4.1	4.0	3.6	3.7
10	NaN	NaN	4.0	3.1	2.0	1.1	1.0	NaN	NaN	2.1	2.5	2.9	3.9	4.7	4.4	4.4	4.5	4.6
11	NaN	5.4	4.7	4.3	3.1	2.1	1.7	NaN	NaN	1.7	2.1	2.3	3.0	3.9	4.1	4.5	4.8	5.0
12	NaN	4.8	4.8	4.8	4.0	3.0	2.6	NaN	NaN	1.4	1.7	1.8	2.5	3.0	3.2	4.1	4.6	5.0
13	NaN	3.7	4.2	4.7	4.4	3.8	3.4	NaN	2.1	1.4	1.5	1.3	1.9	2.4	2.5	3.1	3.8	4.5
14	NaN	2.8	3.1	3.8	4.3	4.2	4.0	NaN	2.9	1.7	1.5	1.0	1.5	2.0	1.9	2.5	2.9	3.7
15	NaN	2.2	2.3	2.8	3.5	3.9	4.2	NaN	3.5	2.4	2.0	0.9	1.3	1.6	1.5	2.0	2.4	3.0
16	NaN	1.7	1.6	2.1	2.5	3.2	3.9	3.7	3.9	2.9	2.6	0.9	1.2	1.3	1.1	1.5	1.9	2.4
17	NaN	1.3	1.3	1.6	1.8	2.3	3.1	3.4	4.1	3.4	3.2	1.4	1.8	1.1	0.8	1.1	1.5	2.0
18	NaN	1.1	0.9	**1.1**	1.4	1.7	2.3	2.6	3.9	3.5	3.7	2.1	2.5	1.6	1.2	1.0	1.3	1.6
19	NaN	1.4	0.8	0.8	0.8	1.2	1.6	1.9	3.2	3.2	3.9	2.7	3.4	**2.5**	2.1	1.6	1.8	1.6
20	NaN	2.5	1.3	0.7	0.7	0.8	1.3	1.4	2.5	2.5	3.8	3.0	4.0	3.2	2.9	2.6	2.9	2.0
21	NaN	3.4	2.4	1.3	0.7	0.6	1.0	1.0	2.0	2.0	3.1	2.7	4.0	3.8	3.5	3.3	3.7	3.0
22	NaN	4.1	3.4	2.4	1.5	0.8	0.9	0.7	1.5	1.4	2.3	2.2	3.7	3.7	3.8	4.0	4.5	3.8
23	NaN	4.1	4.0	3.4	2.5	1.8	1.3	0.6	1.2	1.0	1.8	1.6	2.7	3.1	3.6	4.1	4.8	4.4
24	NaN	3.5	4.1	3.9	3.3	2.6	2.1	1.1	1.2	0.7	1.4	1.1	2.1	2.4	2.8	3.6	4.6	4.6
25	NaN	2.6	3.5	4.0	3.8	3.5	2.9	NaN	1.8	0.6	1.1	0.6	1.6	1.7	2.1	2.7	4.0	4.3

Figure 7: Screenshot of excel spreadsheet for the digitized 1900 tide gauge record. Conditional formatting used for a quality check. Red boxes indicate relatively high numbers and blue boxes indicate relatively low numbers with the intensity of color indicating the magnitude of the number. Numbers that were written in red in the handwritten record were digitized as "NaN" in the excel sheet.



Engineer,

United States Engineer Office,

Georgetown, South Carolina, June 27, 1905,

Superintendent of the Coast & Geodetic Survey,

Washington, D. C.

Sir:

In compliance with instructions received from Captain G P Howell, Corps of Engineers, U. S. A., Officer in charge of the district, Charleston, S. C., there is shipped you by Express this date, the following tide gauge records, from automatic gauge station at North Island, Entrance to Winyah Bay, South Carolina.: all contained in one box:-

From May, 7th, 1898 to Dec. 22, 1898,
From Dec. 28, 1898 to Dec. 28, 1899,
From Dec. 28, 1899 to Jan. 5, 1901,
From Jan. 6, 1901 to Jan. 20, 1902,
From Jan. 20, 1902 to Dec. 16, 1902,
From Dec. 16, 1902 to Jan. 1, 1904,
From Jan. 1, 1904 to Jan. 1, 1905: EXCEPT from Jan. 6th to 21st, 1901 and Feb. 21st to Feb. 29th, 1901, which were kept out on account of temporary inaccuracy of the Gauge.

The Zero of the Gauge refers to these Bench-Marks: B.M., 8.19' elevation above mean low water: Cross cut in stone door sill of North Island Light-House.

B.M., 10.19' elevation above mean low water: North-east corner of cistern at Assistant Engineer's residence--cross cut in brick.

The blue line on the record sheets represents the mean low water in connection with which the Gauge has been operated.

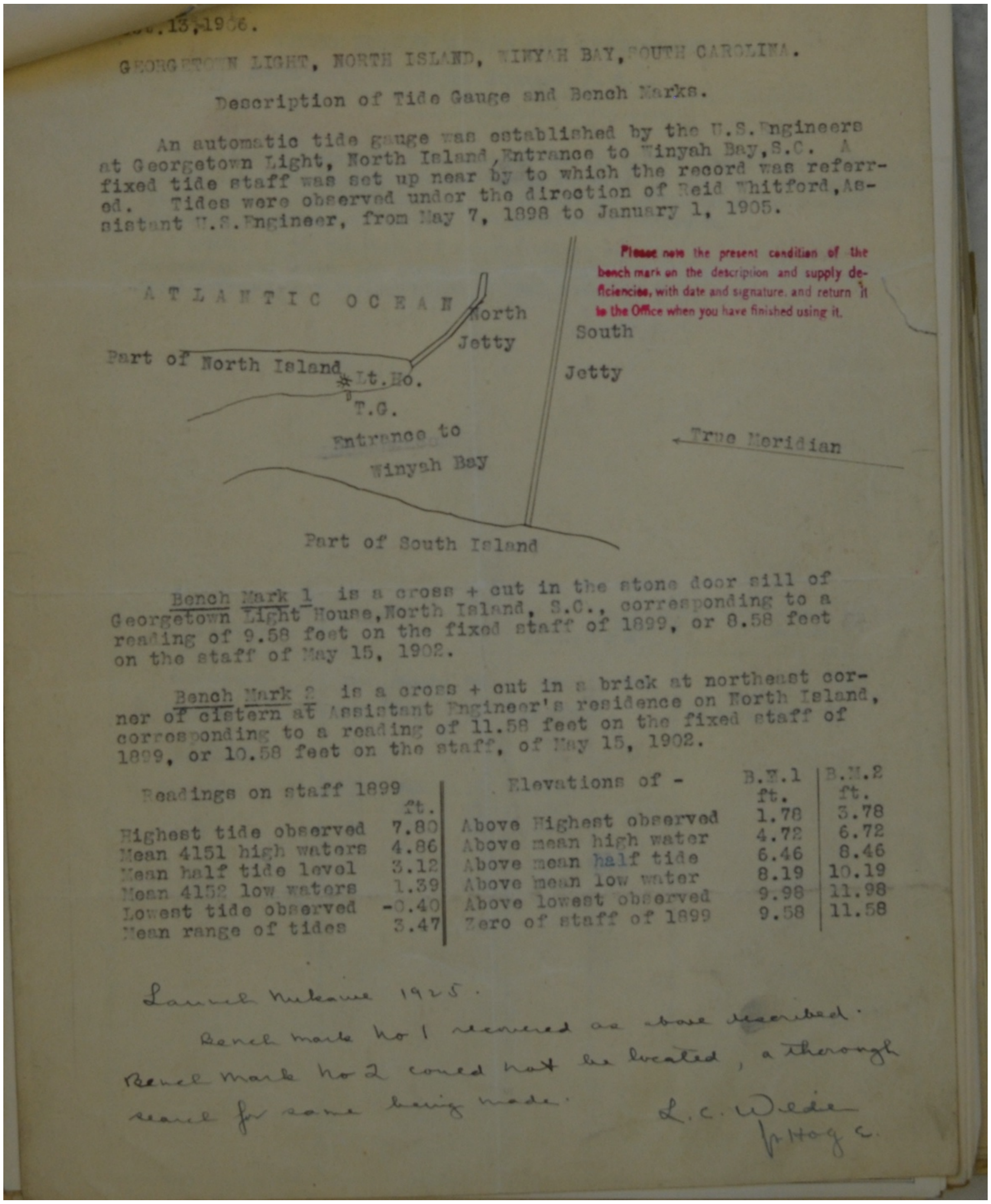
Very Respectfully, Yours,

Reid Whitford

U.S. Assistant Engineer.

(No. 1284, W.B. Gauges, 1905.)

Figure 8: Photograph of documentation of Georgetown Lighthouse tide gauge record from the U.S. Engineers describing the length of the record and the relationship between the tide gauge record and the associated benchmark.



[illegible] 13, 1906.

GEORGETOWN LIGHT, NORTH ISLAND, WINYAH BAY, SOUTH CAROLINA.

Description of Tide Gauge and Bench Marks.

An automatic tide gauge was established by the U.S. Engineers at Georgetown Light, North Island, Entrance to Winyah Bay, S.C. A fixed tide staff was set up near by to which the record was referred. Tides were observed under the direction of Reid Whitford, Assistant U.S. Engineer, from May 7, 1898 to January 1, 1905.

Please note the present condition of the bench mark on the description and supply deficiencies, with date and signature, and return it to the Office when you have finished using it.

Bench Mark 1 is a cross + cut in the stone door sill of Georgetown Light House, North Island, S.C., corresponding to a reading of 9.58 feet on the fixed staff of 1899, or 8.58 feet on the staff of May 15, 1902.

Bench Mark 2 is a cross + cut in a brick at northeast corner of cistern at Assistant Engineer's residence on North Island, corresponding to a reading of 11.58 feet on the fixed staff of 1899, or 10.58 feet on the staff, of May 15, 1902.

Readings on staff 1899	ft.	Elevations of -	B.M.1 ft.	B.M.2 ft.
Highest tide observed	7.80	Above Highest observed	1.78	3.78
Mean 4151 high waters	4.86	Above mean high water	4.72	6.72
Mean half tide level	3.12	Above mean half tide	6.46	8.46
Mean 4152 low waters	1.39	Above mean low water	8.19	10.19
Lowest tide observed	-0.40	Above lowest observed	9.98	11.98
Mean range of tides	3.47	Zero of staff of 1899	9.58	11.58

[illegible] 1925.

Bench mark no 1 recovered as above described.

Bench mark no 2 could not be located, a thorough search for same having made.

L. C. Wilder
[illegible]

Figure 9: Photograph of documentation of Georgetown Lighthouse tide gauge record from the U.S. Engineers describing the location of the benchmarks and the relationship between the reading on the staff and the elevation of the benchmark.

Figure 10: Photograph of historic benchmark located on the sill of Georgetown Lighthouse. Engraving reads "B.M. 8.19 MHW" indicating the elevation of the benchmark in relation to a tidal datum. The elevation of the benchmark was measured with an RTK-GPS and related to the NAVD88.

Figure 11: Satellite image with tide gauges in Wilmington, NC, Myrtle Beach, SC, Georgetown, SC and Charleston, SC marked by blue circles. Map of North and South Carolina with tide gauge locations included for larger spatial context.

Legend

1. 901 Front Street

2. Corner of Greenwich Drive and Front Street

3. NOAA Waccamaw River Entrance tide gauge

4. USGS Pee Dee River entrance river gauge

5. Private Dock tide gauge

6. NOAA Sampit River tide gauge

7. Georgetown Harbor and "working waterfront"

Figure 12: Satellite image of Georgetown, SC with tide gauges marked with red circles, river gauges marked with blue circles and established nuisance flooding locations marked with gold circles.

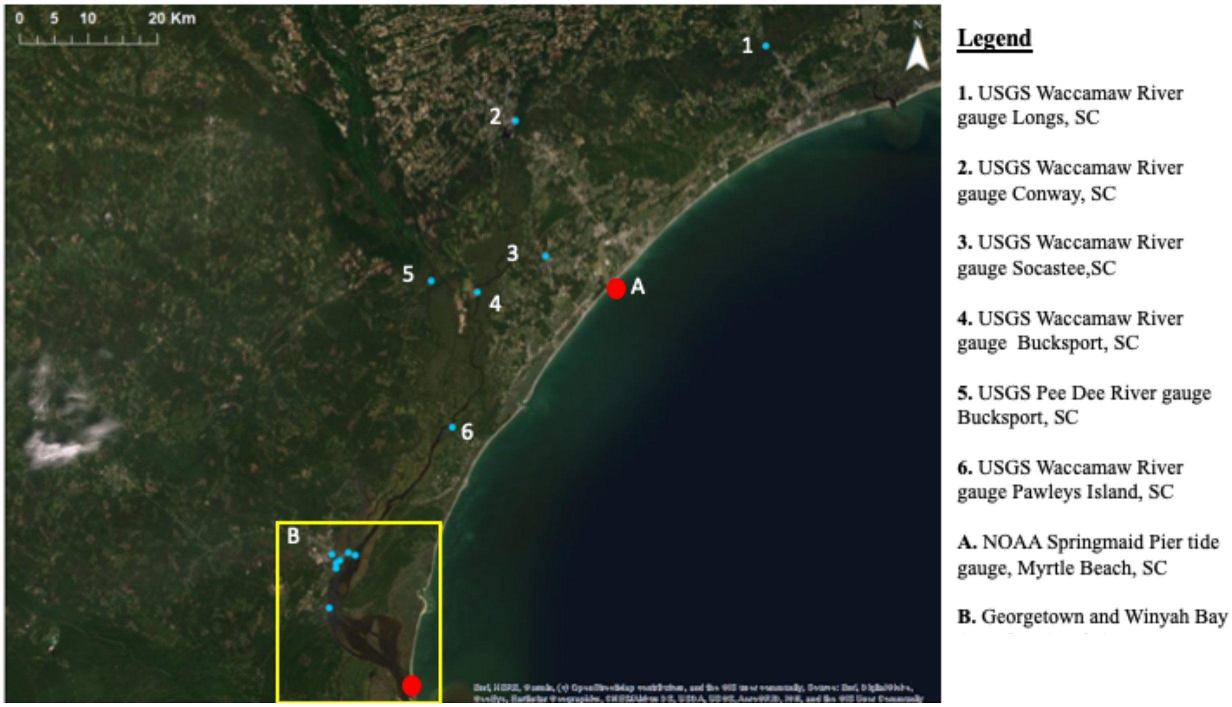


Figure 13: Satellite image of Winyah Bay (yellow box) and Waccamaw River. Tide gauges marked with red circles and river gauges marked with blue circles.

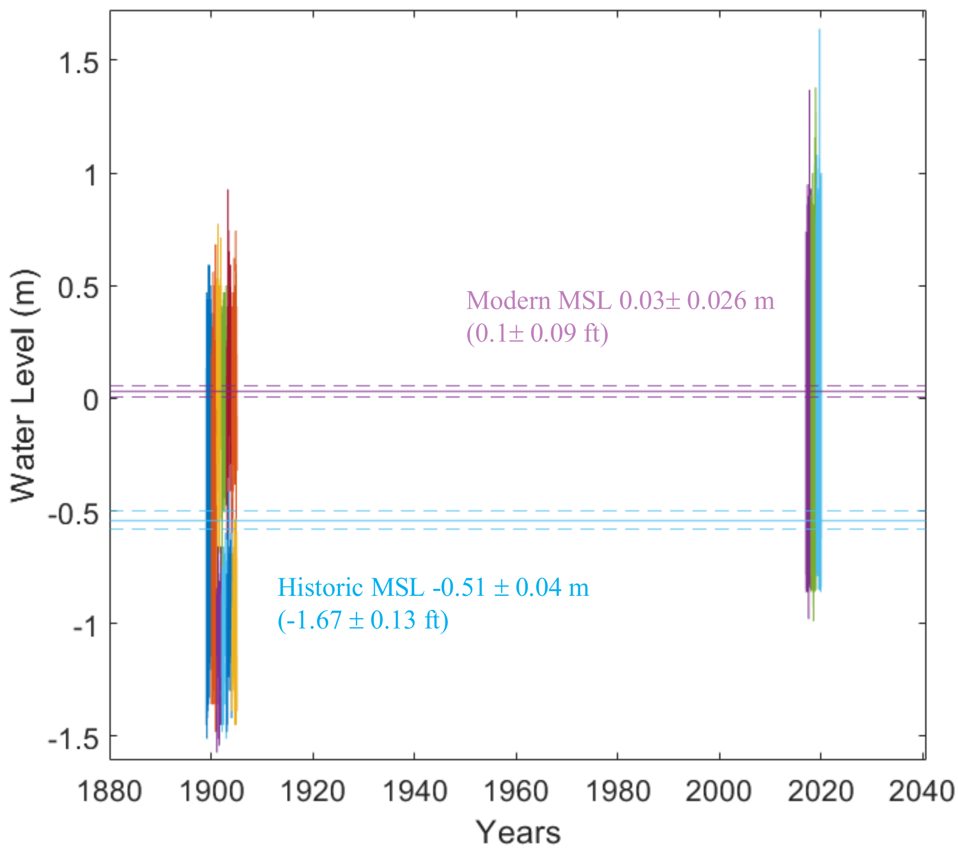


Figure 14: Historic tide gauge records for 1899-1904 and modern water level measurements for 2017-2019 adjusted NAVD88. Each color represents a different yearly dataset (1899 and 1900 hourly water levels, HWL and LWL twice-daily measurements from 1901-1904, and modern water level data from 2017-2019). Solid lines represent the averages of the historic (blue) and modern (purple) data sets. Dashed purple lines show ±0.026 m (± 0.09 ft) estimated error range on modern dataset average and ±0.04 m (± 0.13 ft) estimated error range on historic dataset.

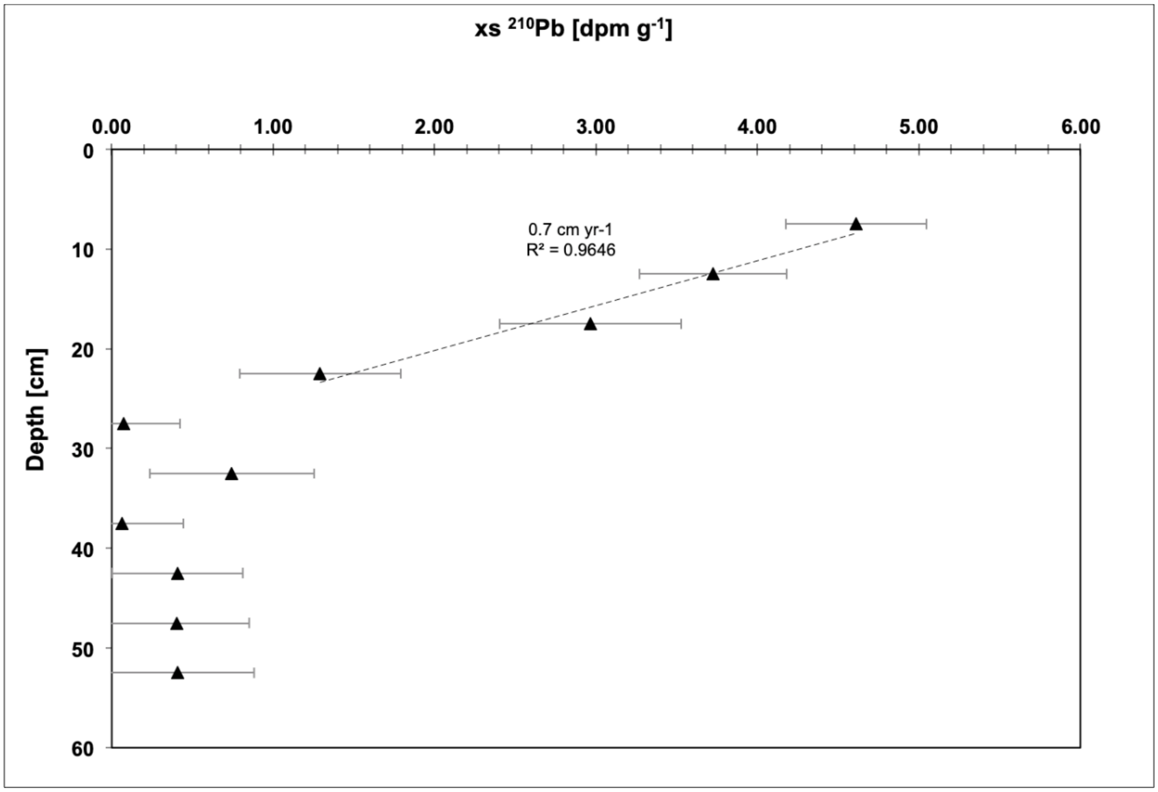


Figure 15: Excess ^{210}Pb curve of sediment core EMB_01and calculated linear sedimentation rate (courtesy of collaborator Dr. Ferdinand Oberle, USGS Santa Cruz). Due to a lack of surface sample, sedimentation rate is assumed to be constant between the surface and the first sample, thus using a linear rate the first sample represents the year 2010. Below 30 cm depth levels are very low and likely background levels. Sample 5 is calculated to represent 1970 based on the linear rate of 0.7 cm/year.

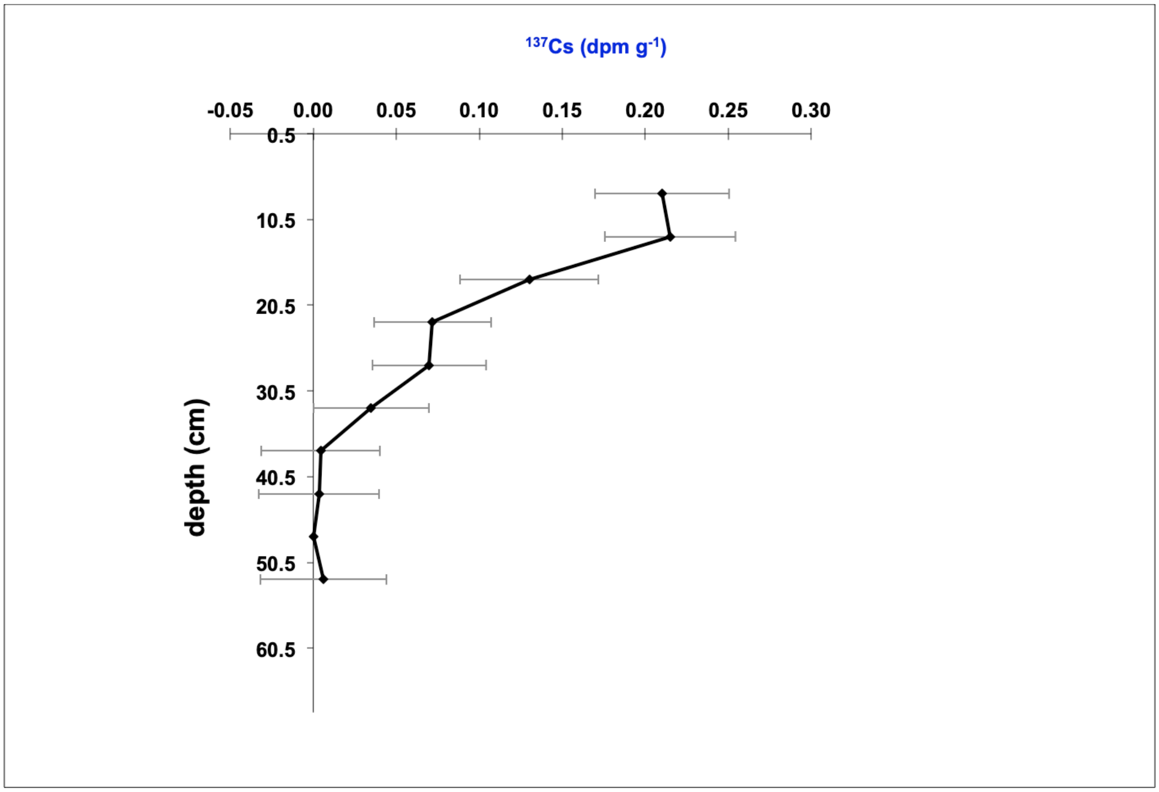


Figure 16: ^{137}Cs curve of sediment core EMB_ (courtesy of collaborator Dr. Ferdinand Oberle, USGS Santa Cruz). These values are low for typical ^{137}Cs measurement but sample 5 (25-30 cm) may represent a weak spike ^{137}Cs which would be associated with the year 1964.

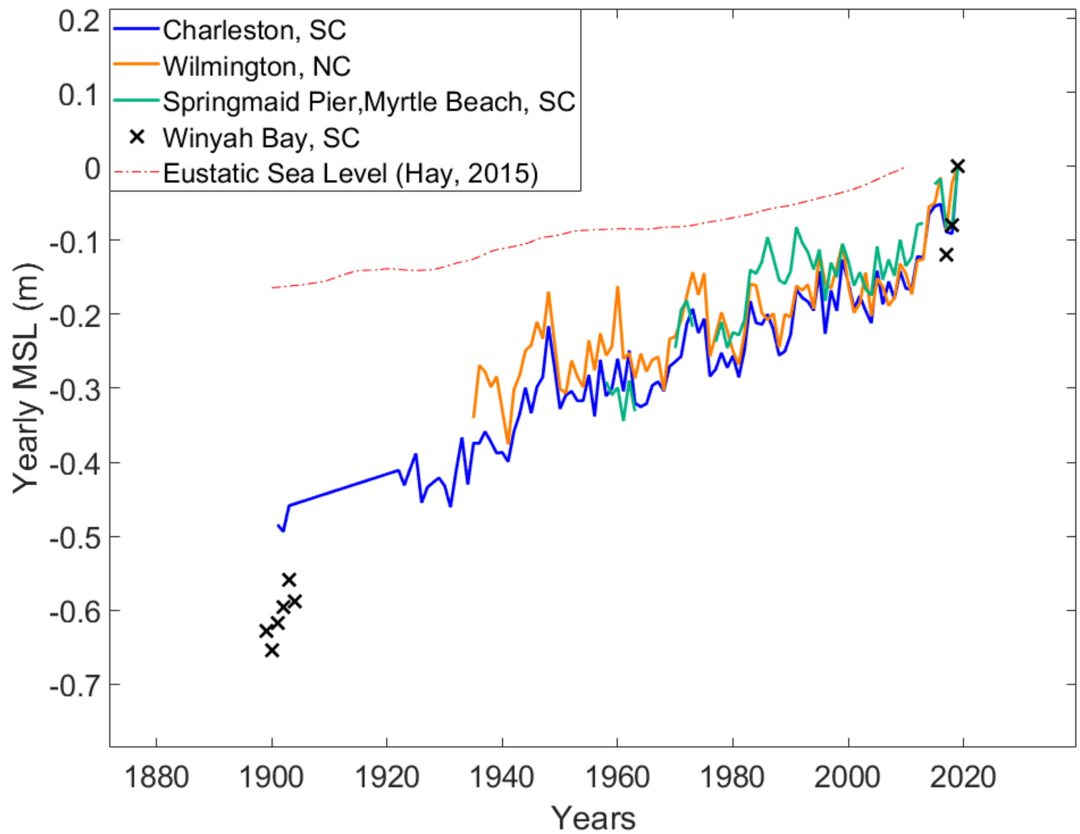


Figure 17: Yearly RSL records for Charleston (Station ID 8665530; NOAA Tides & Currents, 2020), Wilmington (Station ID 8658120; NOAA Tides & Currents, 2020), Myrtle Beach (Station ID 8661070; NOAA Tides & Currents, 2020) and Winyah Bay tide gauges. All four records are adjusted to a 0 m mean sea level (MSL) in the year 2019 and compared to eustatic yearly sea level of Hay (2015).

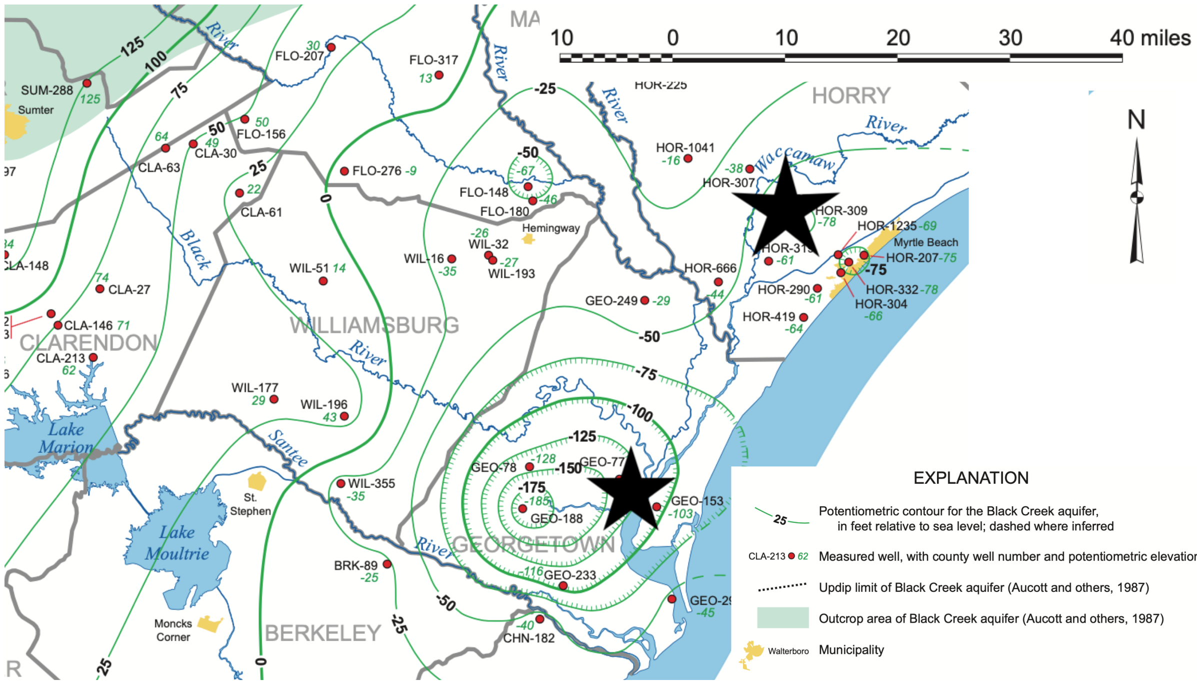


Figure 18: Potentiometric surface map for the Black Creek aquifer in 2012 showing a cone of depression around Georgetown. Green lines are contours of water levels in feet. (Wachob et al., 2015). GEO-0077 and HOR-0309 are marked with black stars.

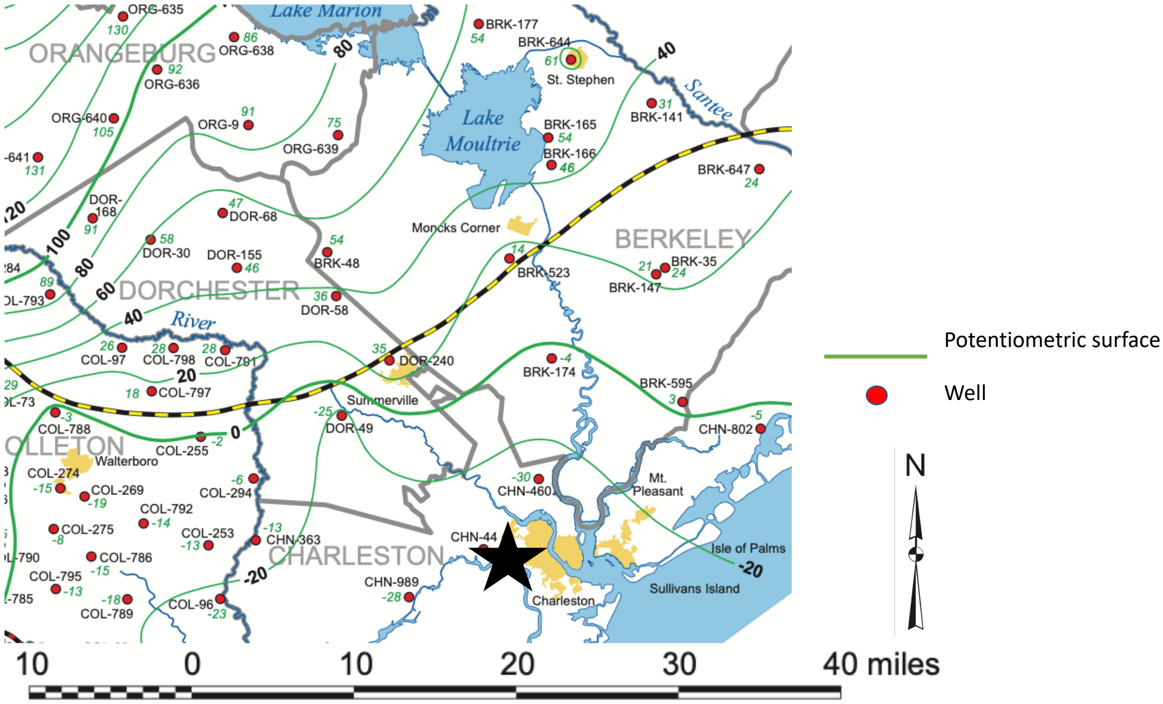


Figure 19: Potentiometric surface map for the Floridan aquifer in 2013. Green lines are contours of water levels in feet and CHN-0044 is denoted with a black star. (Wachob et al., 2015).

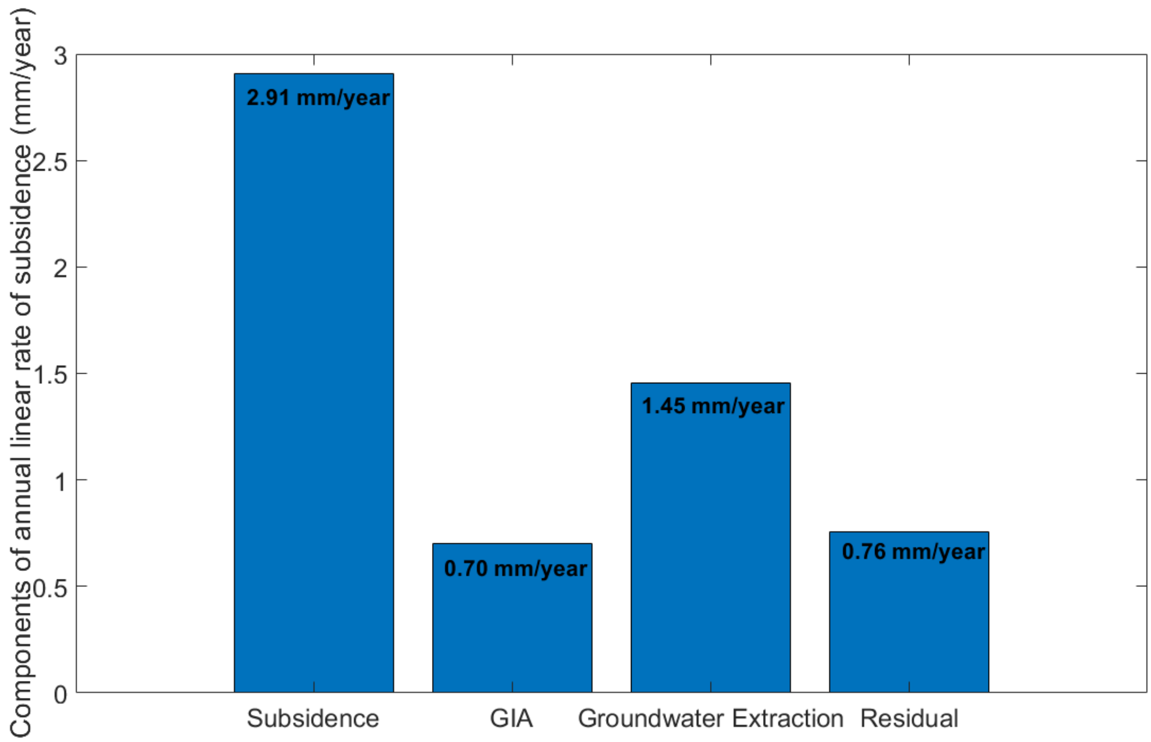


Figure 20: Components of calculated subsidence rate of 2.91 mm/year contributing to long-term linear RSL rise rate in Winyah Bay from 1899-2019 and their approximate contributions. Subsidence calculated by subtracting 20th century average eustatic sea-level rise rate from long-term relative sea-level rise rate at Georgetown Lighthouse. Glacial-Isostatic Adjustment (GIA) estimated from Snay (2020) as 0.7 mm/year. Groundwater extraction calculated based on 50% of total subsidence rate based on Kaegar (2016). Residual component of subsidence calculated as GIA and Groundwater Extraction components subtracted from the overall subsidence rate.

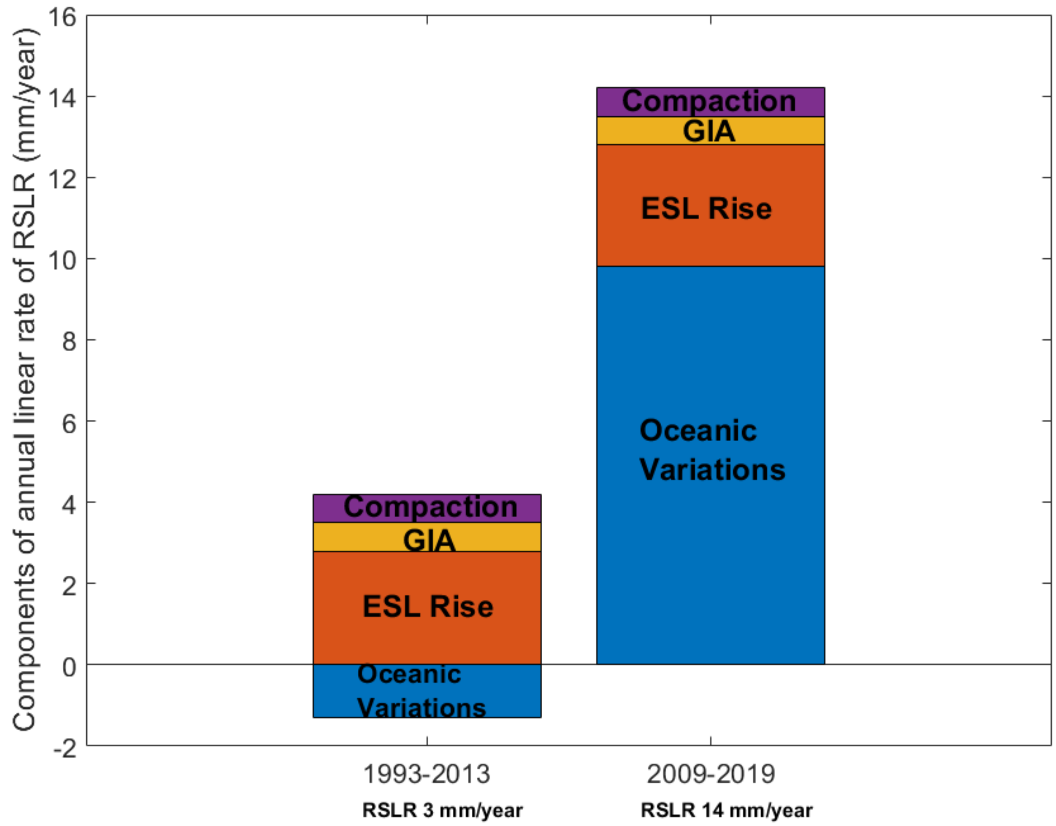


Figure 21: Comparison of rate of relative sea level rise (RSLR) in Charleston and the magnitude of the components that contribute to the overall trends over 1993-2013 and 2009-2019. Subsidence rates from GPS measurements (Nevada Geodetic Laboratory, 2020), Glacial-Isostatic Adjustment (GIA) estimated from Snay (2020) as 0.7 mm/year, Compaction estimated as residual subsidence after estimated GIA contribution is removed. Eustatic sea level rise rates are calculated from satellite data for 2009-2019 data (NASA, 2020) and from satellite and tide gauge networks for 1993-2013 because satellite data was not available for the beginning of this period (Church and White, 2011). Oceanic variation data from "Interannual Variation Since 1990" at the Charleston Tide Gauge (Station ID: 8665530; NOAA Tides & Currents, 2020).

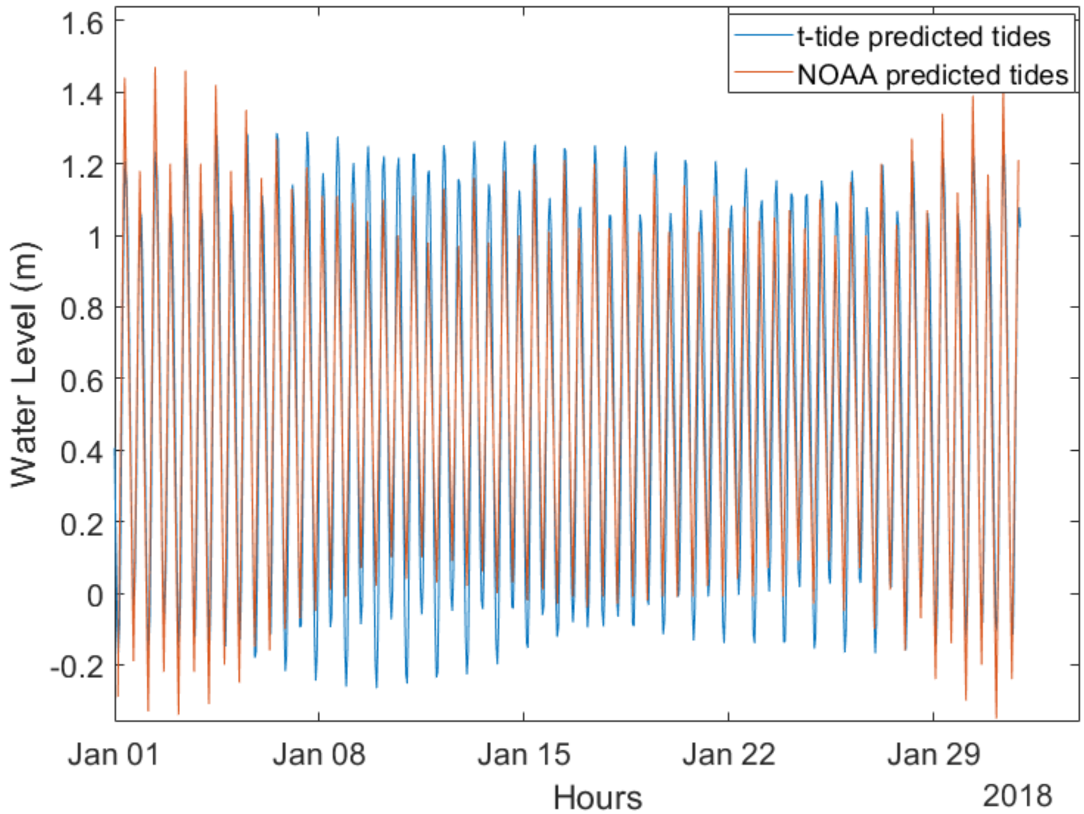


Figure 22: Comparison of T-TIDE predicted tides at the Private Dock and NOAA predicted tides at Sampit River entrance (Station ID 8662926; Fig. 12) for January 2018. Timing of tides is the same between NOAA prediction and T-TIDE prediction. Amplitude is slightly different between the two locations but this difference may be caused by the slight difference in location.

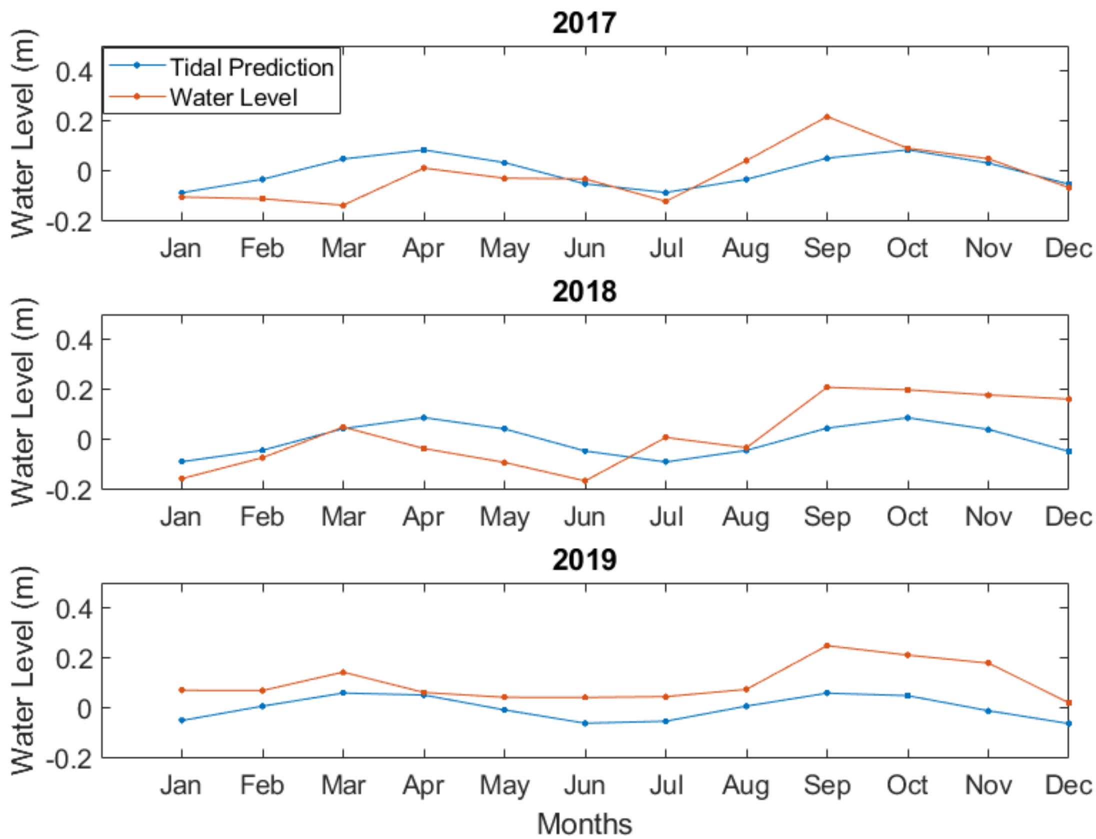


Figure 23: Monthly averaged predicted tides for the Georgetown Lighthouse (calculated with T-TIDE) and water-level from the NERR station from 2017-2019 to show seasonal trends similar between the two data sets.

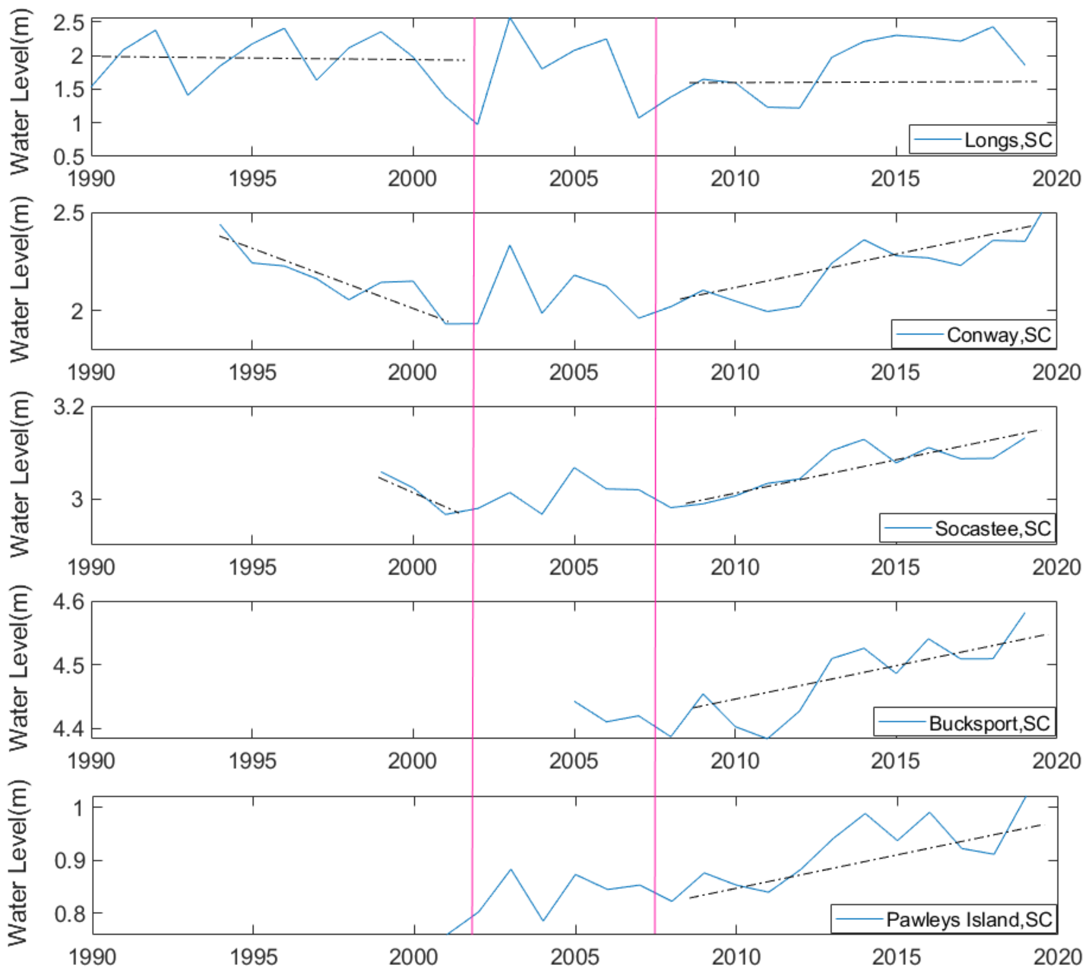


Figure 24: Inter-annual variations in water level in the Waccamaw River from 1990-2019. Visually interpreted trends noted in dotted lines and pink lines note period of stagnation or minor fluctuations (USGS, 2020).

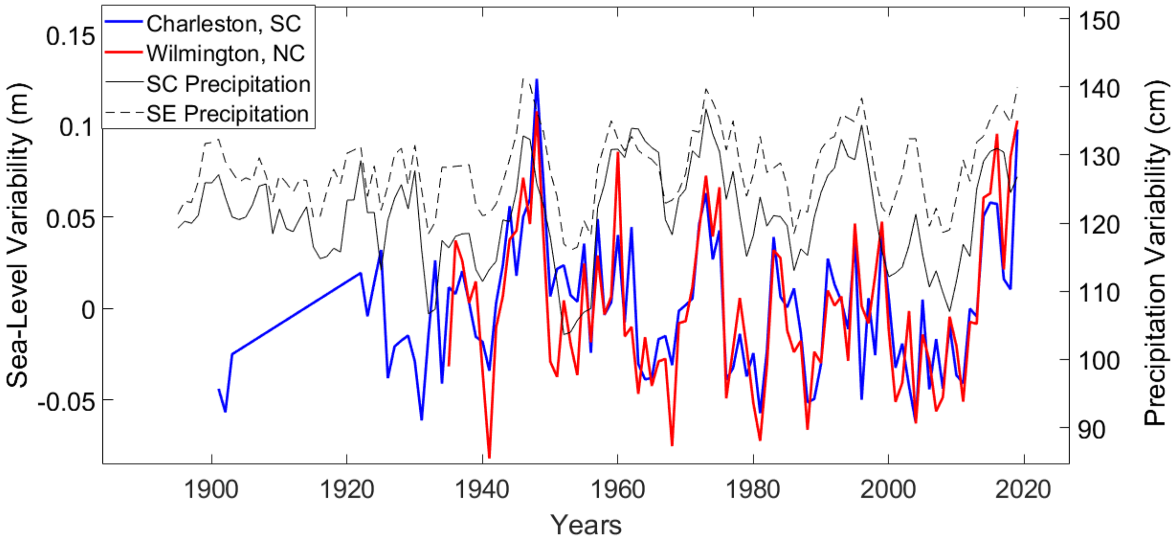


Figure 25: Detrended yearly sea level in Wilmington, NC and Charleston, SC and yearly South Carolina and Southeastern US regional precipitation showing decadal and annual variability common between the two data sets.

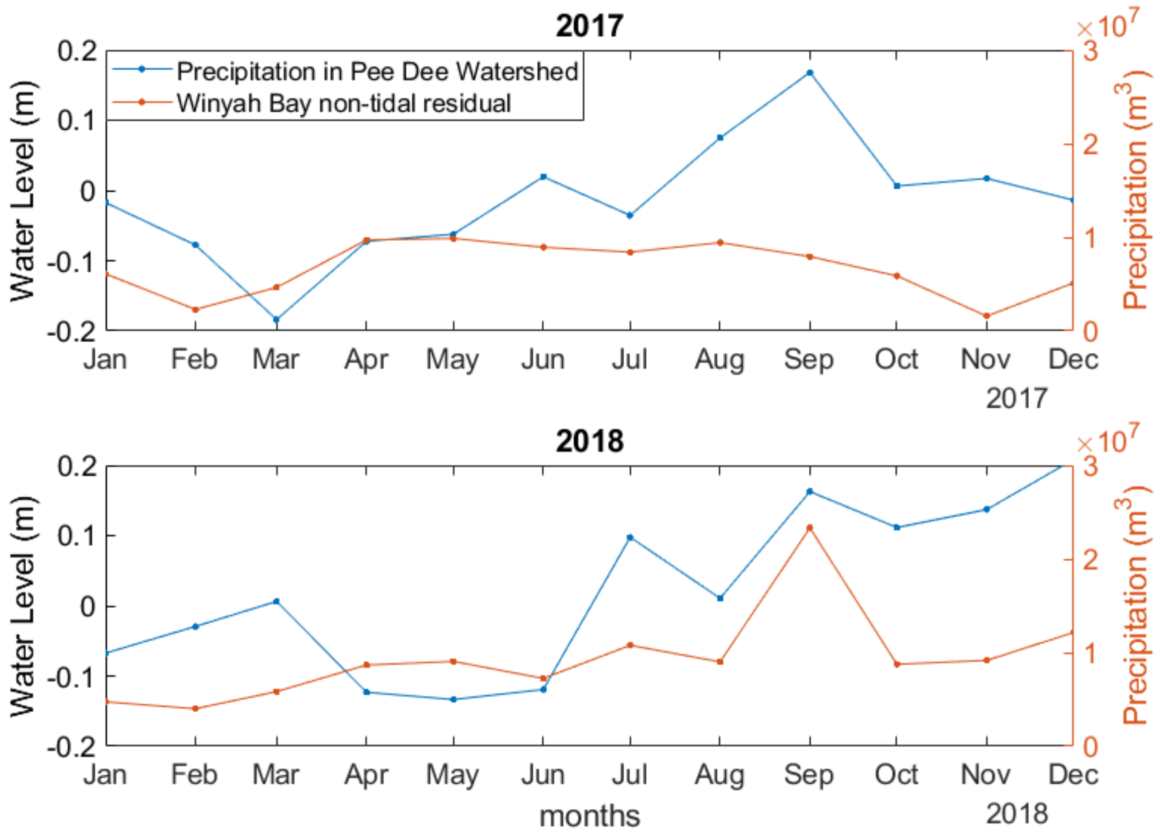


Figure 26: Monthly average non-tidal residual water level at the NERR station (NERR, 2020) in Winyah Bay and monthly average precipitation in the Pee Dee watershed (NOAA NWS, 2020) for the years 2017-2018. Note the increase in precipitation from July-October during both years which corresponds with high water levels in Winyah Bay. High water levels in September of both years associated with hurricanes (Michael in 2017 and Florence in 2018).

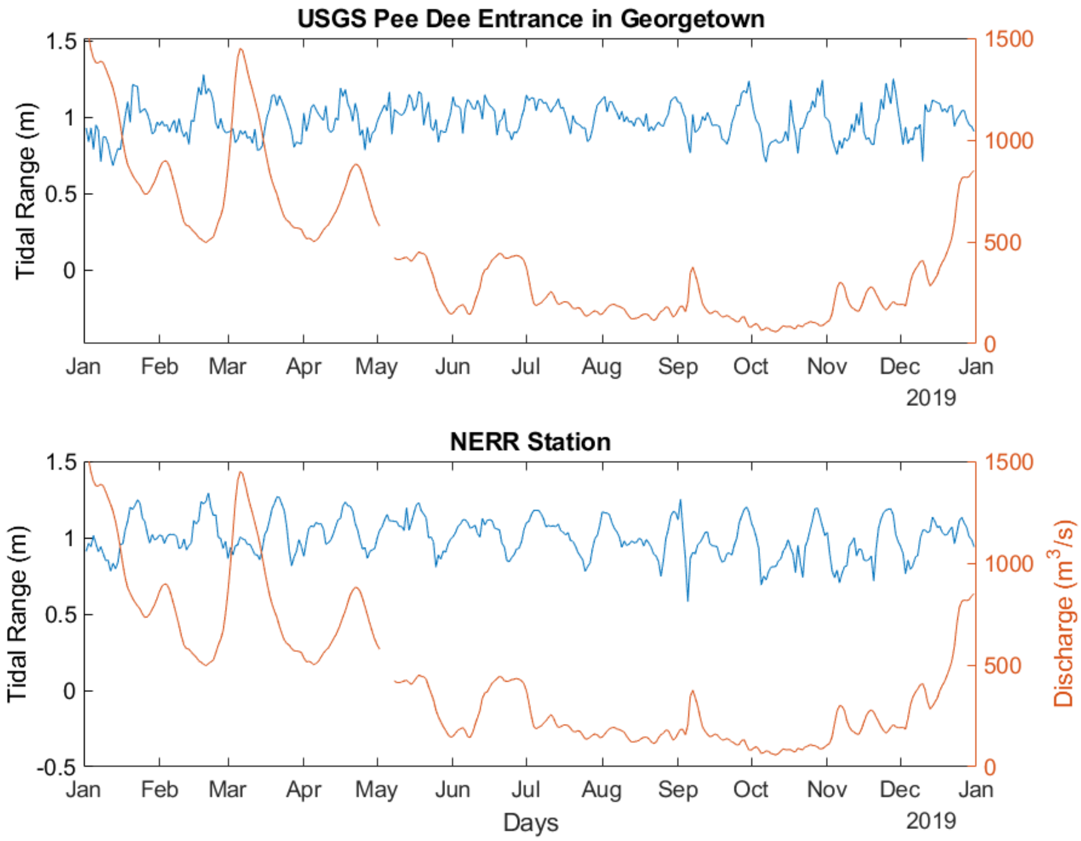


Figure 27: Daily average discharge for the Pee Dee River at Bucksport and daily average tidal range for the USGS gauge at the Pee Dee River in Georgetown (top) and daily average discharge for the Pee Dee River at Bucksport the NERR station in Winyah Bay (bottom) (for gauge locations, see Fig. 13). Note that during some high discharge events there is a concurrent decrease in tidal range at both the NERR station (NERR, 2020) and the USGS station at the entrance to the Pee Dee at Georgetown (USGS, 2020).

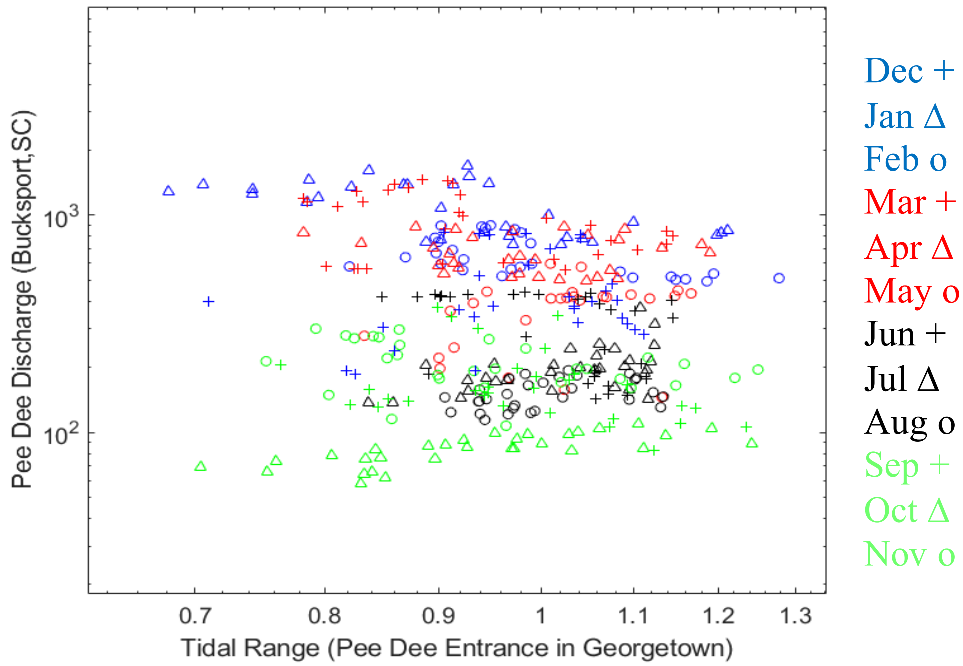


Figure 28: Daily average discharge for the Pee Dee River at Bucksport related to daily average tidal range for the year 2019 at the USGS station at the entrance to the Pee Dee River near Georgetown. Data are separated into months by shape and seasons by color. Note the possible linear trends during January, April and May that could indicate the role high discharge events play in lowering tidal range in Winyah Bay.

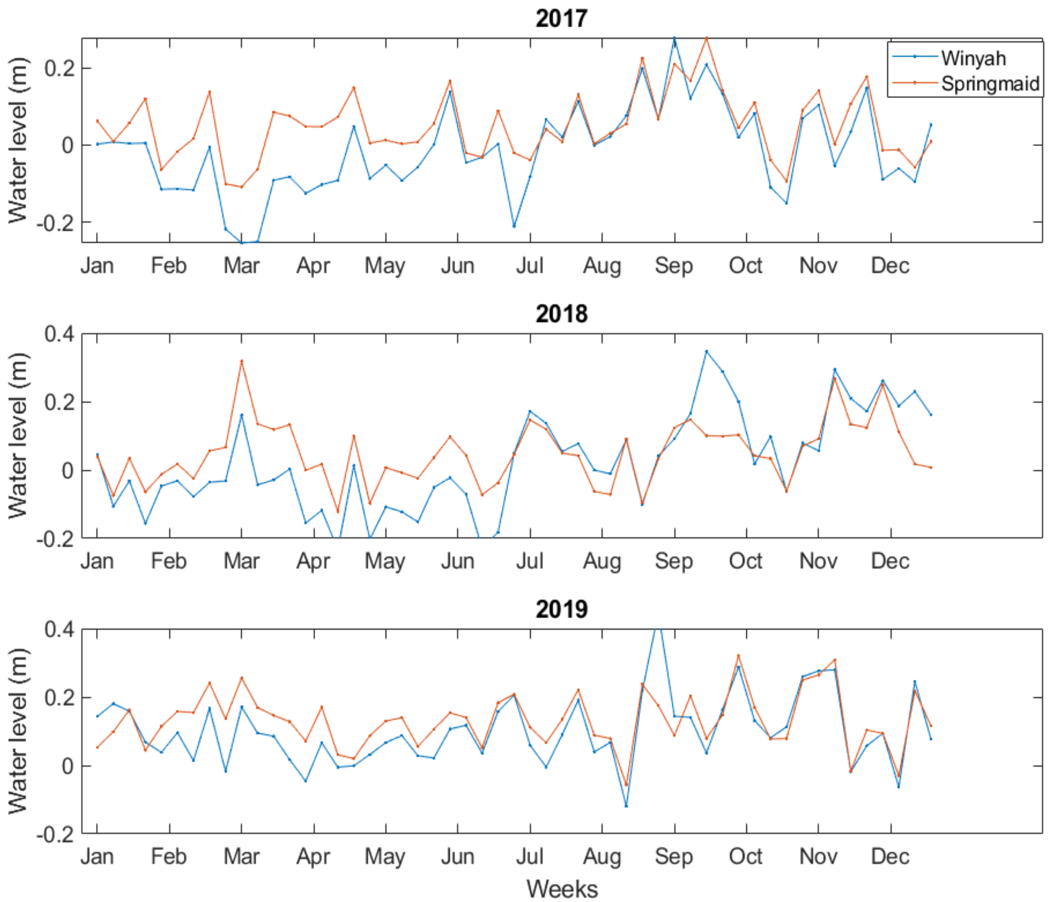


Figure 29: Seasonal trends in weekly average coastal non-tidal residual water levels at Springmaid Pier in Myrtle Beach (NOAA Tides & Currents, 2020) and weekly average Winyah Bay non-tidal residual water levels at NERR station in Winyah Bay, both with mean sea level removed (NERR, 2020). Note that while Springmaid water levels are generally higher, the timing of fluctuations between the two data sets are the same.

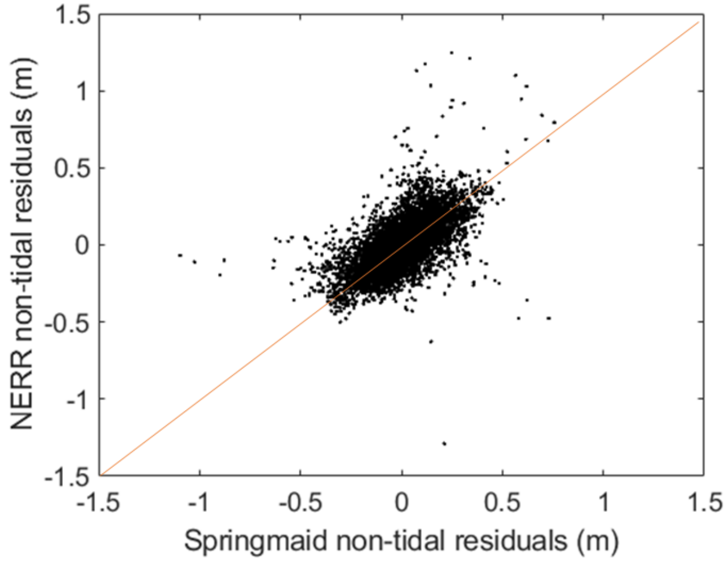


Figure 30: NERR non-tidal residuals (NERR, 2020) and Springmaid non-tidal residuals (NOAA Tides & Currents, 2020) plotted with orange 1:1 line showing ideal linear relationship in order to examine the relationship between coastal water level and water level in the bay. Note that most data falls on this 1:1 line that shows that the data fluctuate in similar ways but there are residual data points that fall above the line that may represent high discharge events in Winyah Bay.

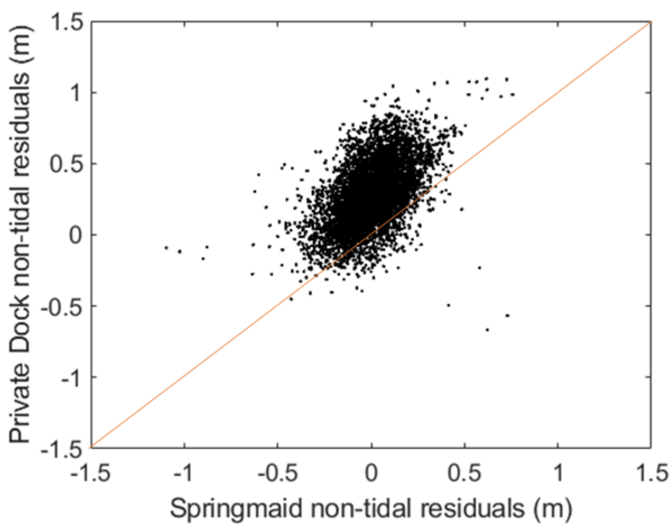


Figure 31: Private Dock non-tidal residuals and Springmaid non-tidal residuals (NOAA Tides & Currents, 2020) plotted with orange 1:1 line showing ideal linear relationship in order to examine the relationship between coastal water level and water level in the back of Winyah Bay. Note that most data is linear but the slope is steeper than that of the 1:1 line indicating the water level is consistently higher in the back of Winyah Bay near Georgetown than it is in the coastal ocean at Springmaid Pier.

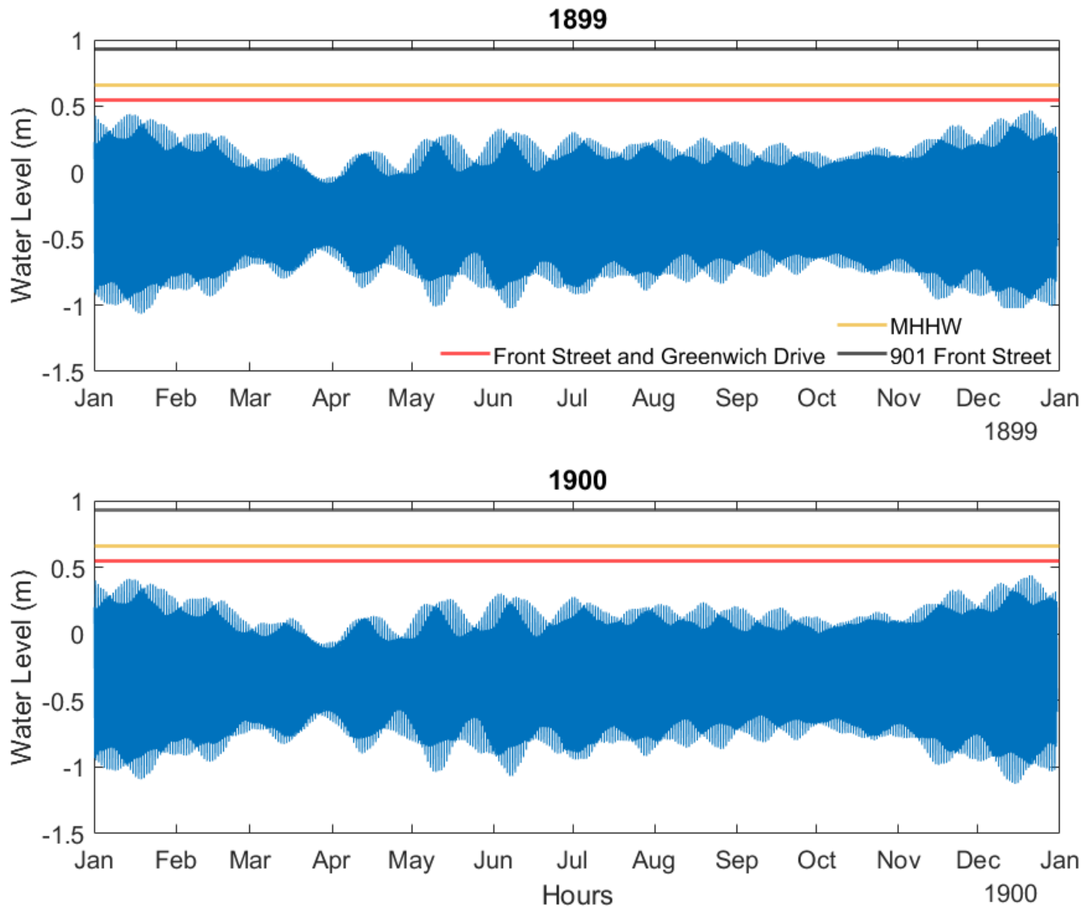


Figure 32: Tidal modeling from T-TIDE for Private Dock for the years 1899-1900 exhibiting there would have been no flooding due to tides and RSL alone at the modern elevation levels of 901 Front Street (black line), MHHW (gold line) or Front Street and Greenwich Drive (red line).

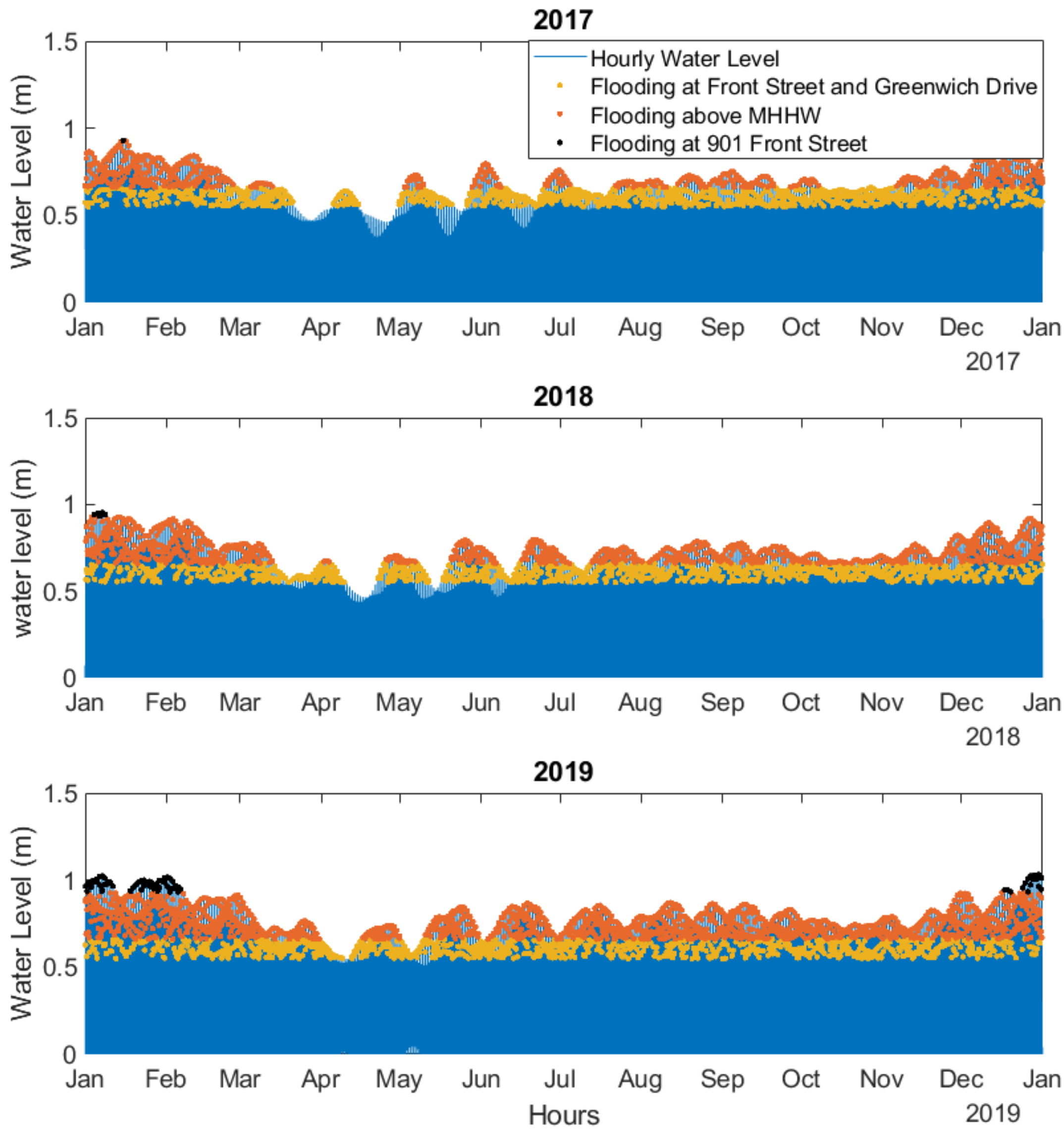


Figure 33: Tidal modeling from T-TIDE showing modern nuisance flooding in Georgetown from 2017-2019 with corner of Front Street and Greenwich Drive flooding denoted in yellow, MHHW denoted in orange and 901 Front Street denoted in black (see Fig. 12 for locations). Note flooding occurs more times each year at 901 Front Street and that flooding is more prominent from December-March and June-July.

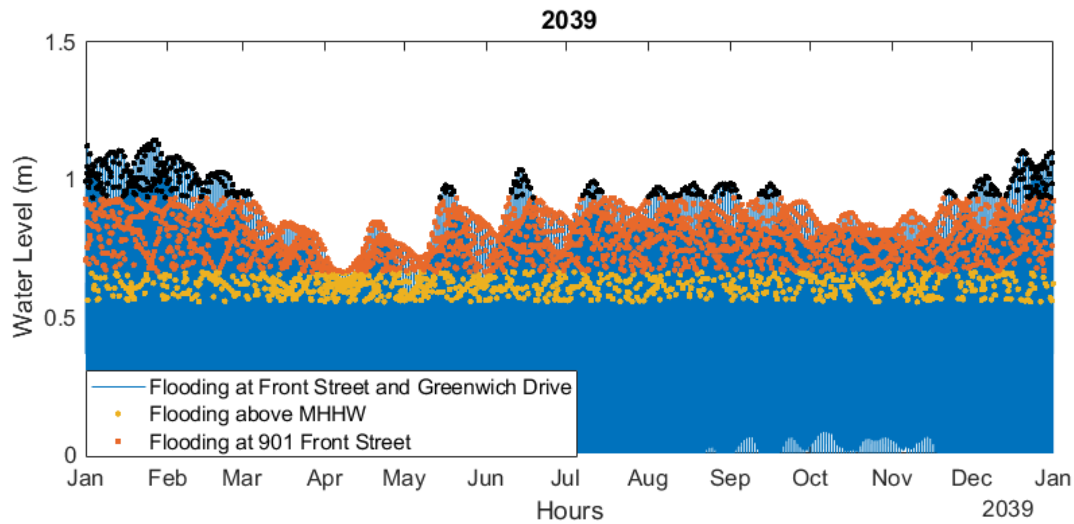


Figure 34: Future tidal prediction for Georgetown with estimated RSL rise, showing flooding at both locations and above current MHHW in 2039.

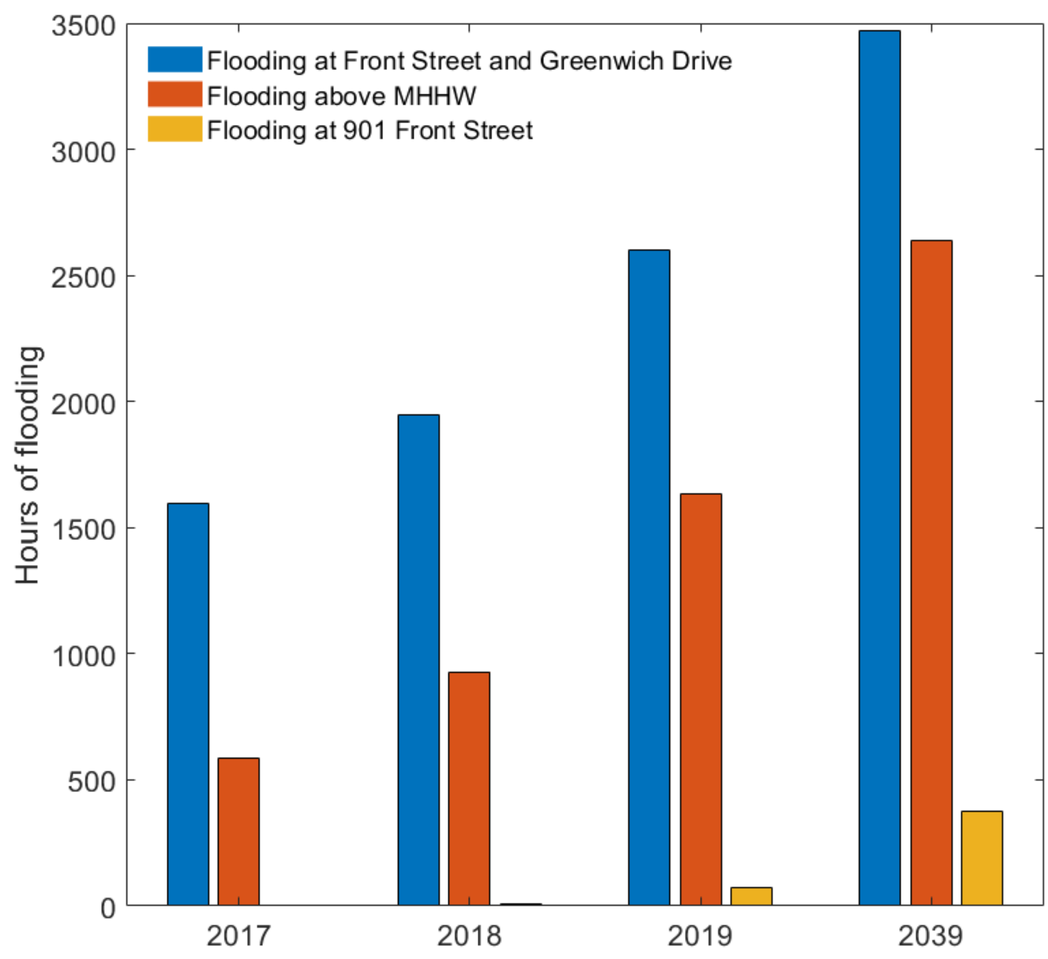


Figure 35: Bar plot showing the duration of nuisance flooding in hours at the two locations and above current MHHW from 2017-2019 and 2039. Note the increase in duration of flooding each year at all three locations.

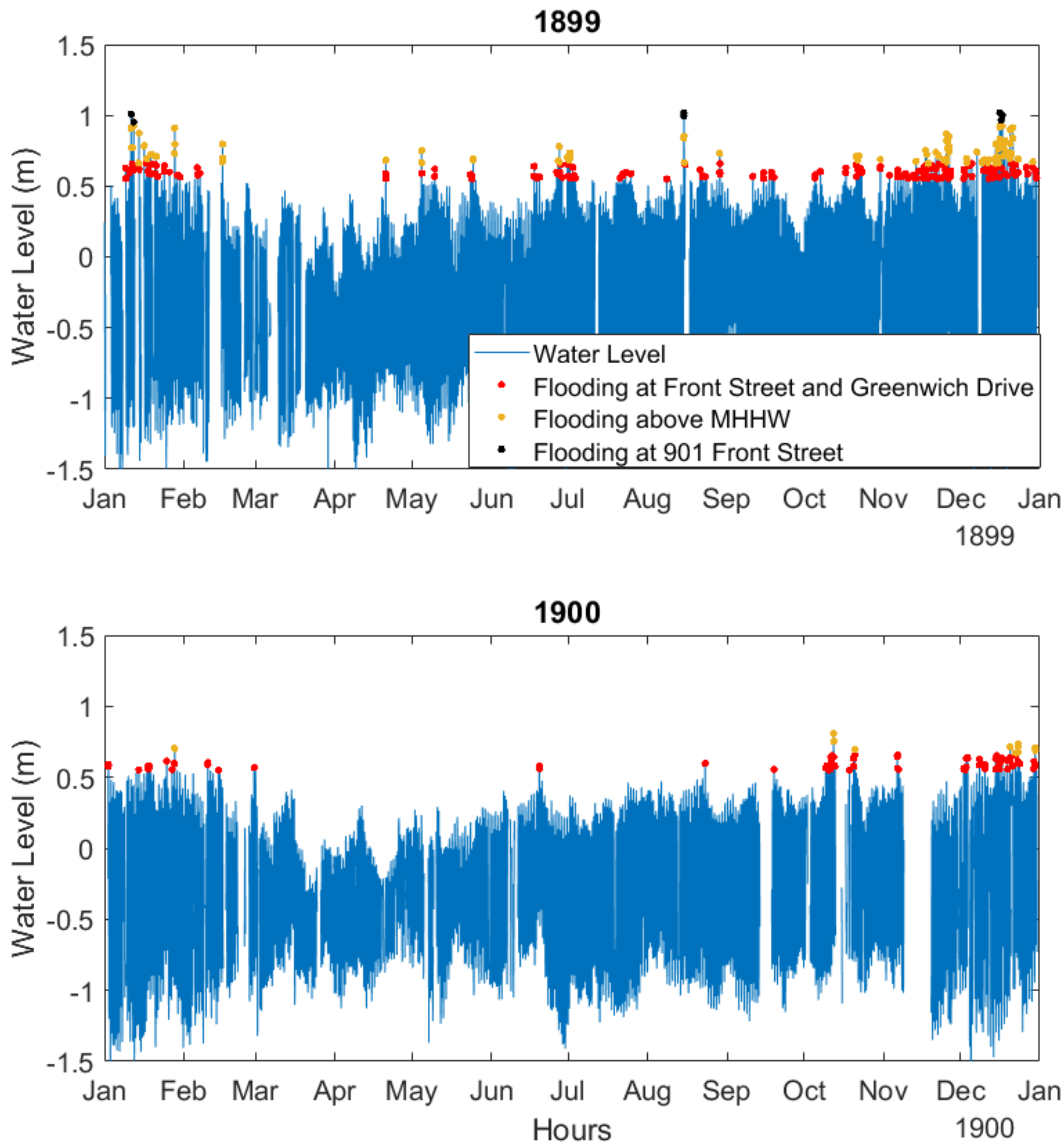


Figure 36: Flooding in Georgetown in 1899 and 1900 modeled as non-tidal water level residuals from the Georgetown Lighthouse record added to the tidal prediction at the Private Dock and the surface water level gradient from the Georgetown Lighthouse to the Private Dock. Blue line represents the water-level modeling and flooding is calculated as occurrence of water level over the measured land elevation level at Front Street and Greenwich Drive (red), 901 Front Street (black) and current MHHW (orange). Note that flooding does occur historically at all three locations occasionally due to a combination of tides, discharge and atmospheric variations such as wind and pressure.

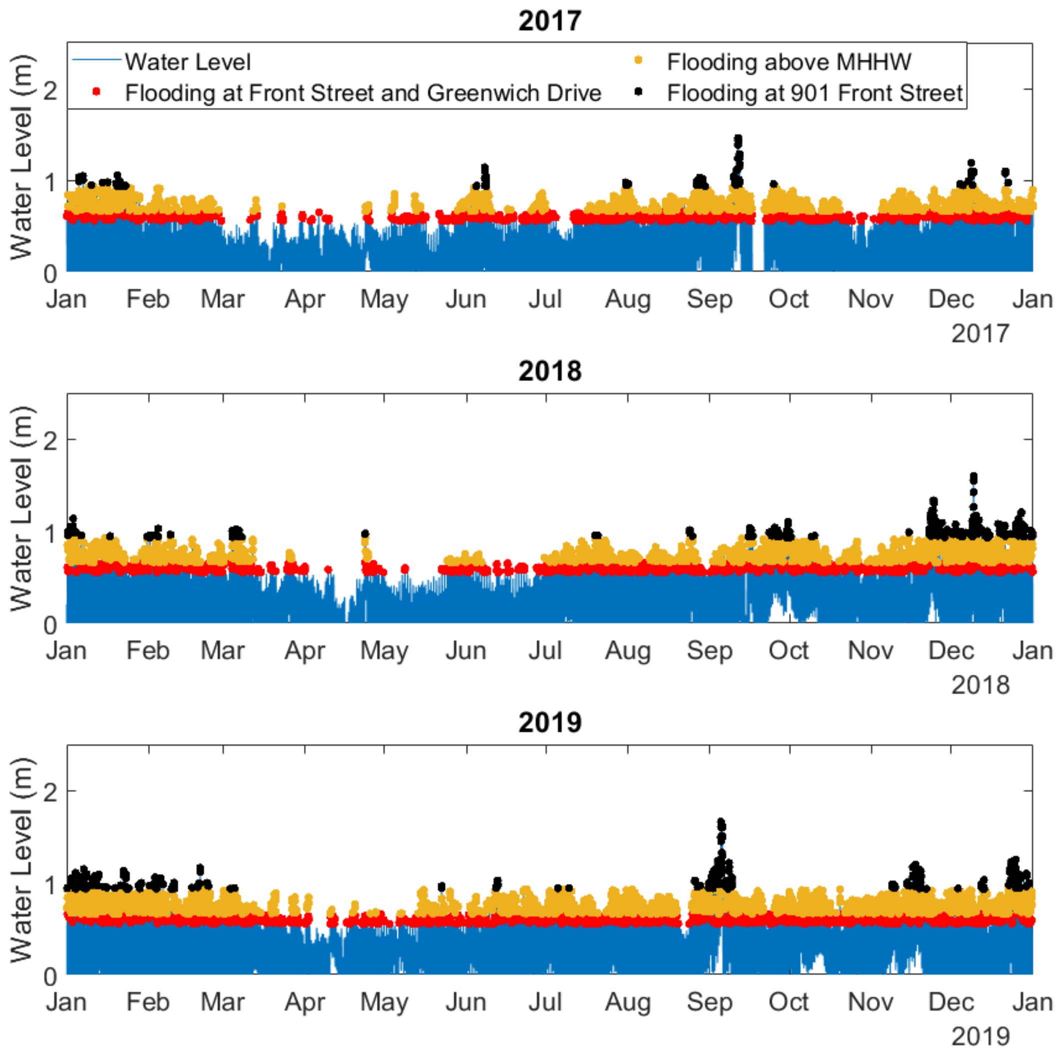


Figure 37: Flooding in Georgetown in 2017-2019 modeled as non-tidal water level residuals from the NERR station record added to the tidal prediction at the Private Dock and the surface water level gradient from the NERR station to the Private Dock. Blue line represents the water-level modeling and flooding is calculated as occurrence of water level over the measured land elevation level at Front Street and Greenwich Drive (red), 901 Front Street (black) and current MHHW (orange). Note that flooding does occur historically at all three locations due to a combination of tides, discharge and atmospheric variations such as wind and pressure. Note that Flooding occurs at 901 Front Street during times of the year when tides are generally higher (from December-March and June-July) and when precipitation and discharge are higher (From September-October).

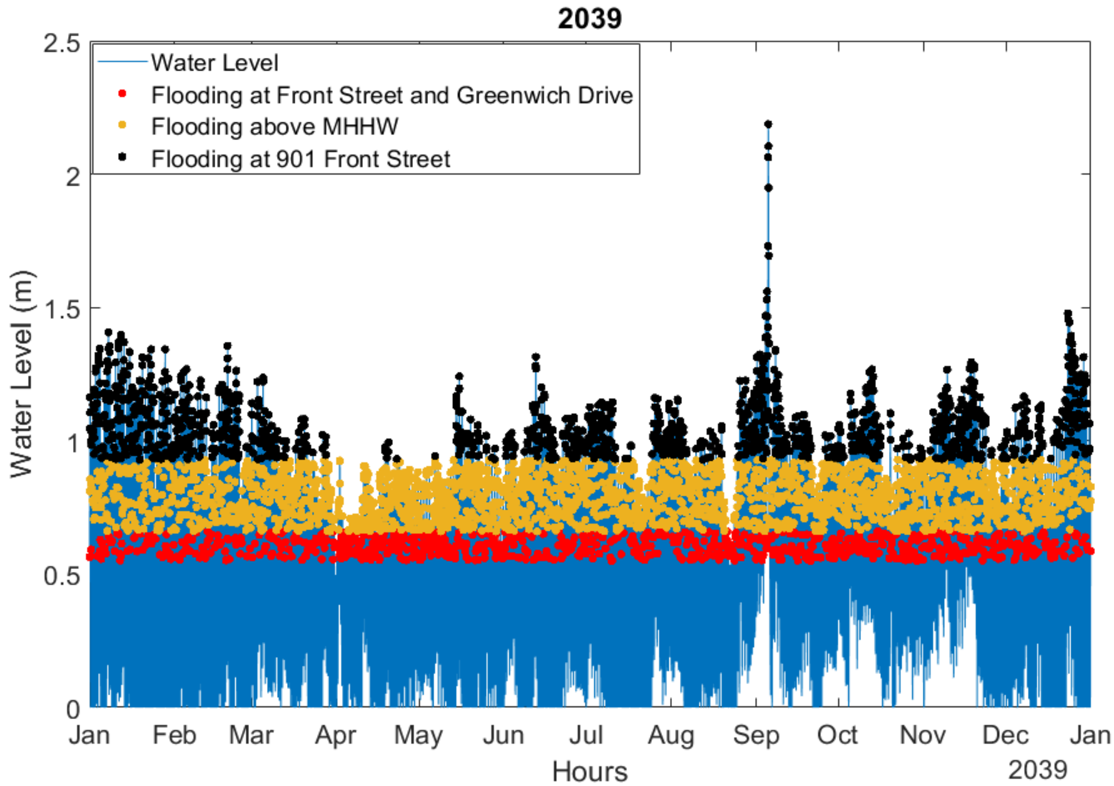


Figure 38: Modeled future flooding in Georgetown for the year 2039 based on a calculated RSL rise (described in text), predicted tides at Private Dock, non-tidal water level residuals from 2019 NERR station record and gradient from NERR station to Private Dock. Blue line represents the water-level modeling and flooding is calculated as occurrence of water level over the measured land elevation level at Front Street and Greenwich Drive (red), 901 Front Street (black) and current MHHW (orange). Note that flooding occurs a majority of the year at all three elevation levels except for when tides are lower from March-May.

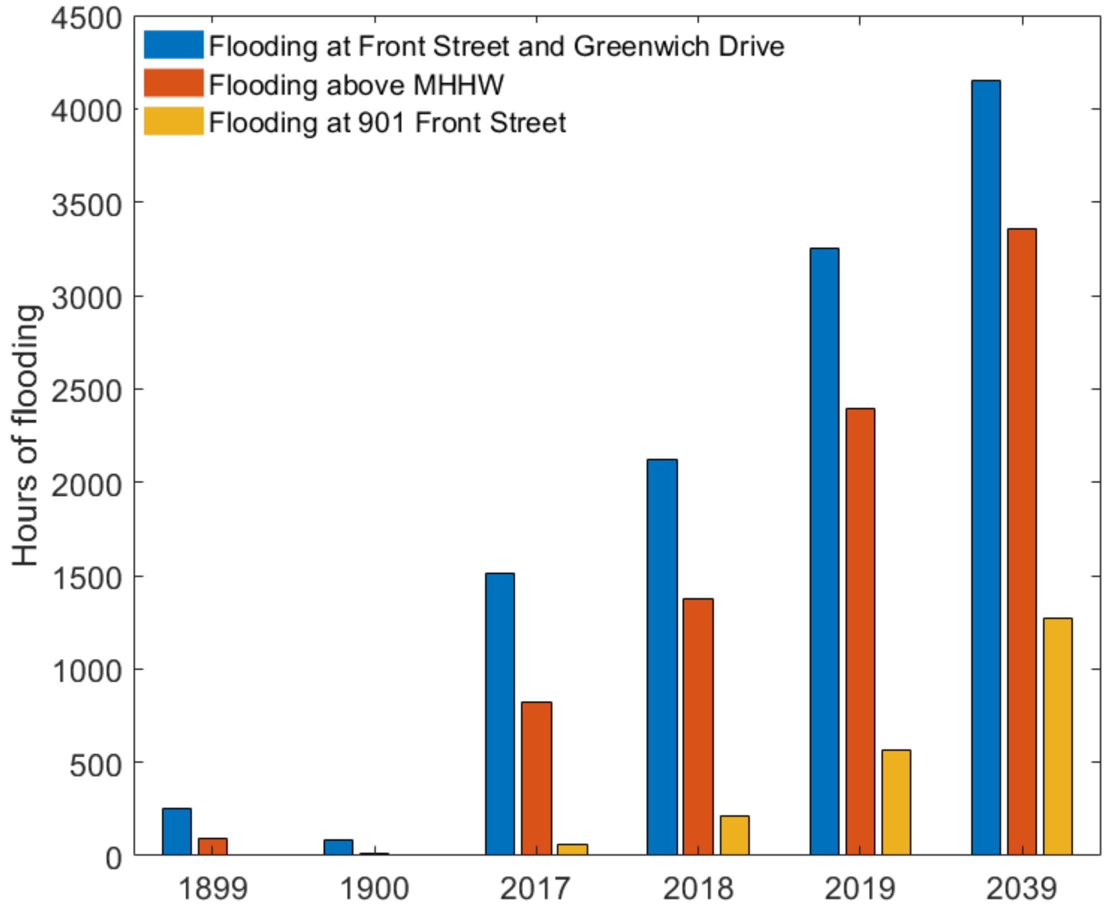


Figure 39: Yearly duration (in hours) flood inundation occurs at each elevation in the historic, modern and future scenarios. Note the strong increase in duration both inter-annually as well as between the historic, modern and future records.

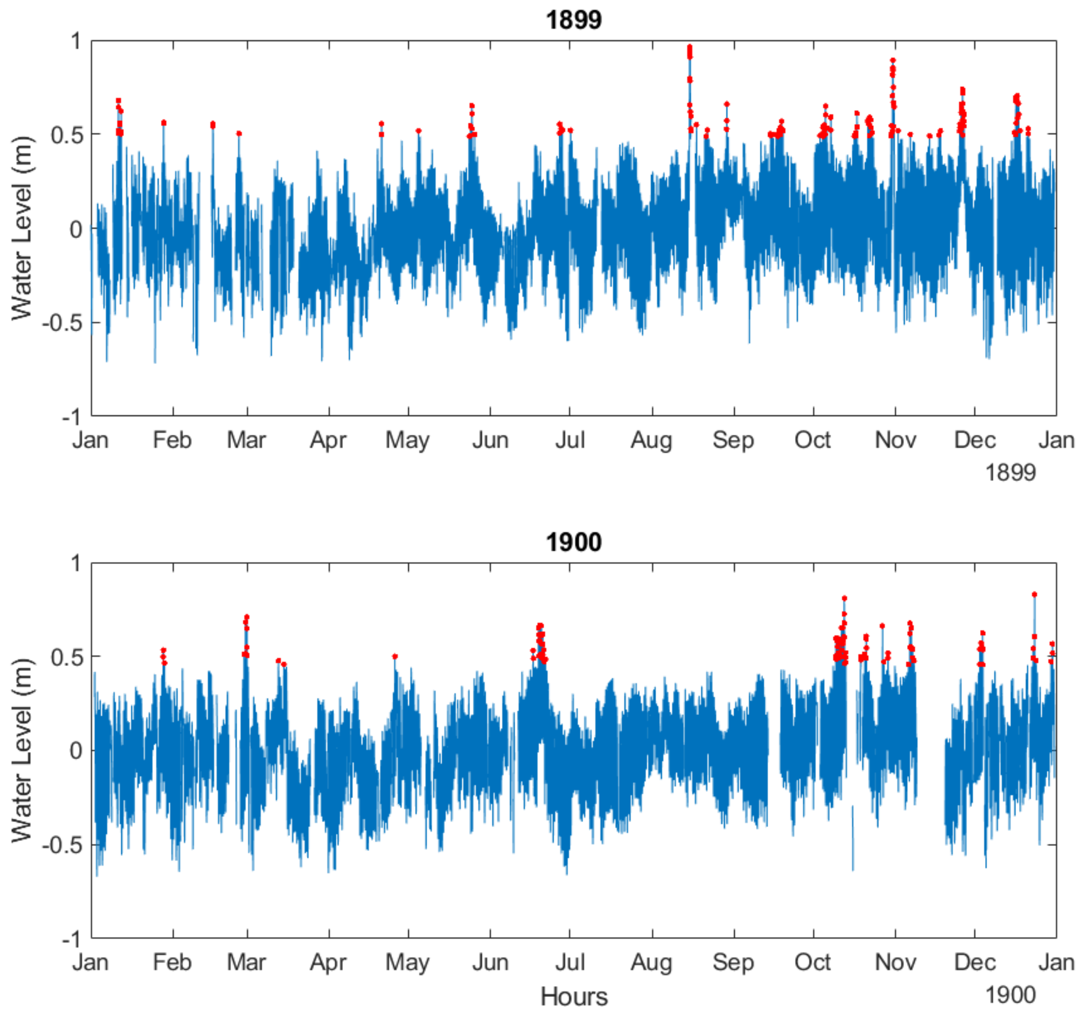


Figure 40: Non-tidal residual water-levels with mean sea level removed (shown in blue) in the 1899 and 1900 tide gauge records. Storm events greater than 2 standard deviations (shown in red). This record of storm events is used to compare the size and number of storm events in the historic record to that in the modern record.

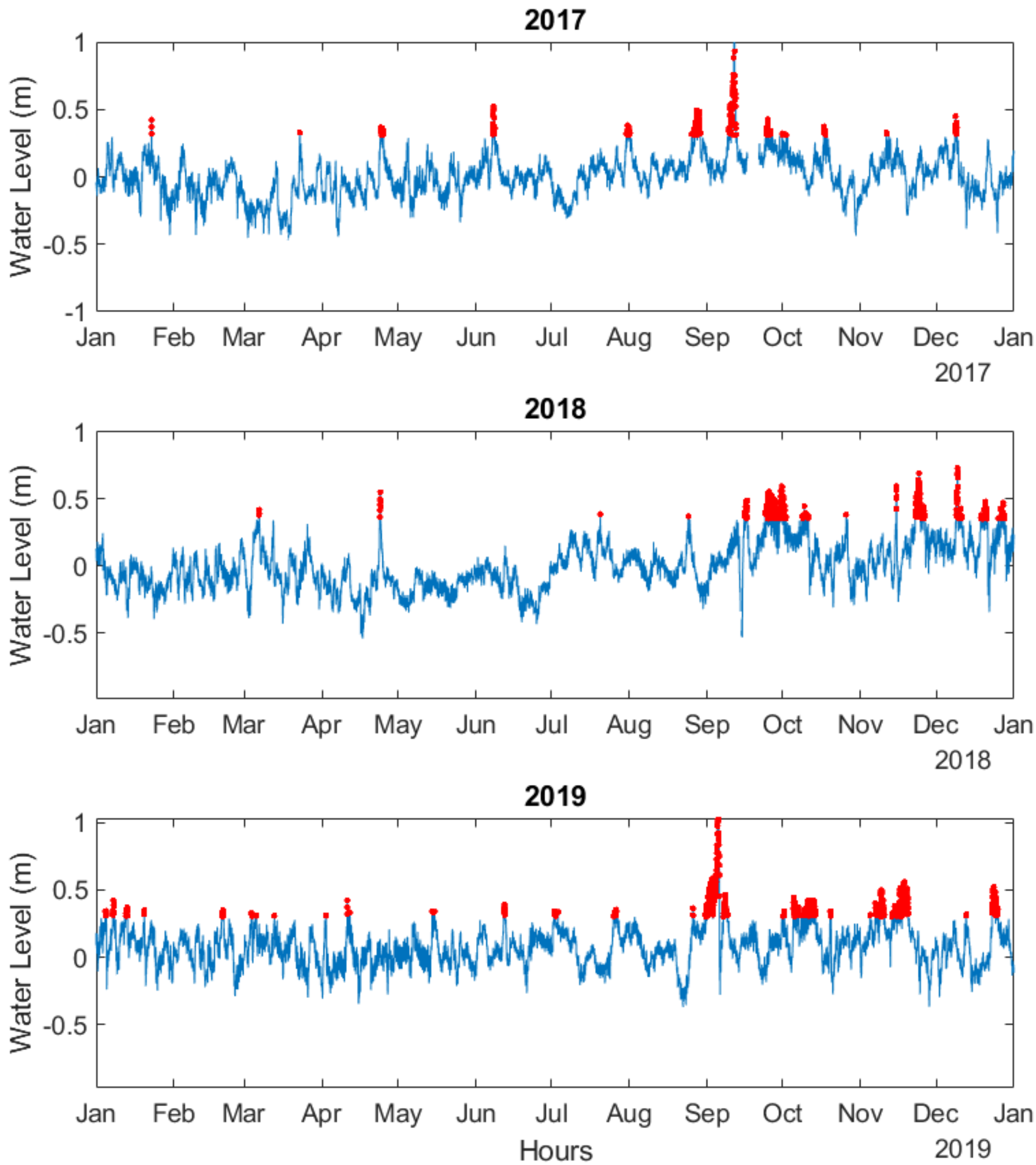


Figure 41: Non-tidal residual water-levels with mean sea level removed (shown in blue) in the 2017-2019 NERR tide gauge records. Storm events greater than 2 standard deviations (shown in red). Note that the sizes of the largest events appear to be the same as those in the historic record (around 1m water level). Also note the different shapes and sizes of water-level responses between the September 2017 (Hurricane Irma) October 2018 (Hurricane Florence) and September 2019 (Hurricane Dorian) storm events.

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APPENDIX

Table 1: Significant tidal constituents and their changes in amplitude and phase over historic time period from 1899-2019 as well as inter-annual changes from 1899-1900 and 2017-2019.

Tidal Constituent	Difference in amplitude 2019-1899 (cm)	Difference in phase 2019-1899	Difference in amplitude 1900-1899 (cm)	Difference in phase 1900-1899	Difference in amplitude 2019-2018 (cm)
O1	-1.14	16.09	-0.61	0.9	-0.1
K1	-0.42	12.09	0.03	1.69	-0.05
N2	0.73	28.51	0.06	3.06	0.61
M2	1.24	26.16	-3.15	4.74	0.11
S2	-1.55	28.97	-0.88	5.3	-0.15
M4	-0.16	-4.83	0.26	1.88	0.15